NEW

All About Space Annual

EXPLORATION | SOLAR SYSTEM | DEEP SPACE
SPACE SCIENCE | FUTURE TECH

250+ amazing space facts

Welcome to the All About Space Annual

"We are all made of star-stuff. We are a way for the universe to know itself." That's one of the late astronomer Carl Sagan's most famous quotes. What did he mean? That every single atom that makes up every molecule that goes into making every cell in your body, was forged billions of years ago in the enormous nuclear furnace of a dying star. To be curious about the space beyond the tiny sphere of our own world is to be interested in your own origins. In All About Space Annual 2015, we look at the endeavours of humankind to explore our cosmic back yard as best we can using great rockets and intrepid probes. But we go far beyond that, peering into the wider universe: we look at a star so big it would engulf most of our Solar System and at the supermassive black hole at the centre of our galaxy. We consider the trillions of moons and planets orbiting the billions of stars in the Milky Way alone, then ask ourselves whether it could be possible that life doesn't exist somewhere else space. We've crammed the next 200 pages with fascinating facts, stunning illustrations and interviews with some of the world's top astronomers and scientists, but we really hope this prompts you to further explore the ceaselessly amazing sphere of space.

All About Space Annual

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Contents

Exploration

Solar System

Deep Space

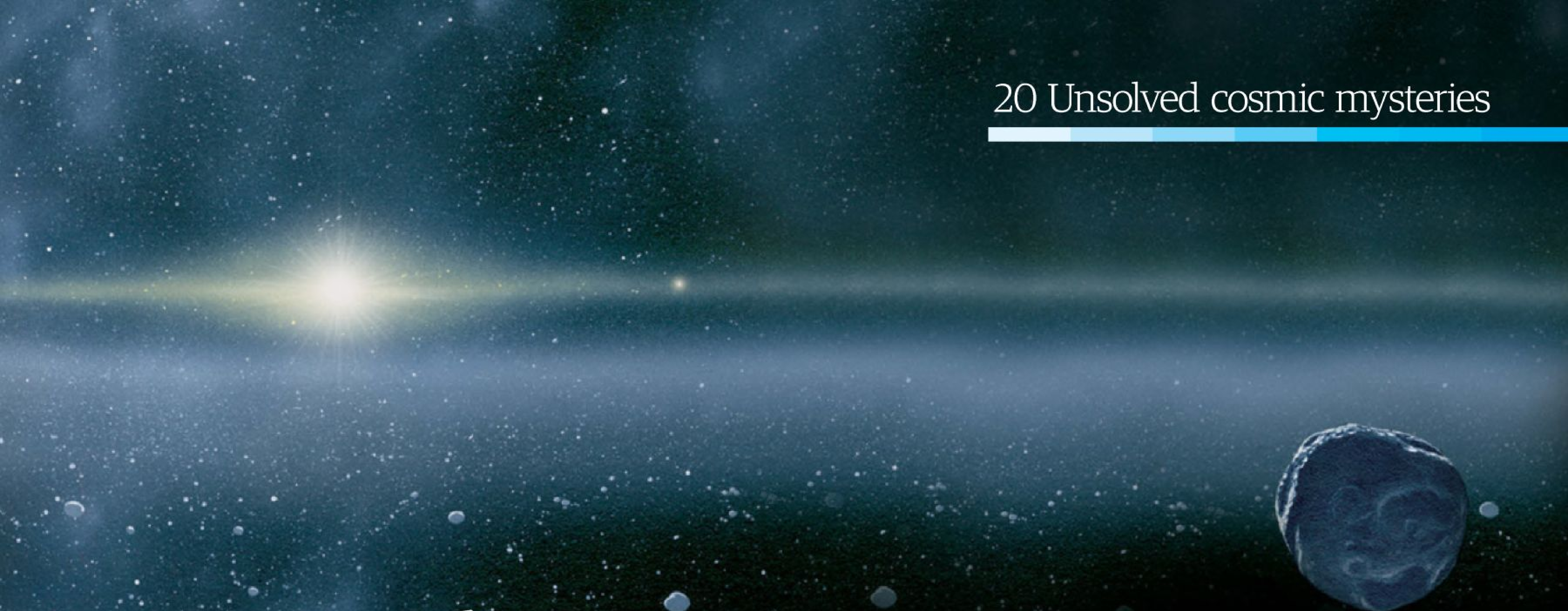
Space Science

Future Tech

"That may have been 'one small step' for Neil, but it's a heck of a big leap for me!"

20 UNSOLVED COSMIC MYSTERIES

White holes, hypergiant stars, Planet X... there are many unexplained mysteries of space, but also some fascinating theories behind them



1 Does Planet X exist?

The Kuiper Belt is a region beyond the Solar System that's 20-times larger and up to 200-times heavier than the asteroid belt. It's also littered with small icy bodies of volatile methane, ammonia and water. Here the number of large objects should be increasing the further through the belt you move, however, that's really not the case at all. In fact the complete opposite happens; the belt all of a sudden drops off, quite drastically, just like a cliff. Meet the Kuiper Cliff – the unexpected outcome with no answer.

The Kuiper Belt isn't just home to small bodies – dwarf planets Pluto, Makemake and Haumea are also thrown into the mix. However some scientists, including Patryk Lykawka of Kobe University in Japan, think that the Kuiper Cliff can be explained by some planet, perhaps the size of Earth or Mars, lurking somewhere as yet unseen by us, whose gravitational attraction is causing the Kuiper Belt to behave in such a way.

The idea of a Planet X turned up the discovery of Pluto and for many years it was thought that a world, larger than Pluto, must exist undiscovered beyond it. Suggestions that this so-called Planet X was influencing Neptune's orbit were quickly put to bed. However, the Kuiper Cliff has reopened the whole Planet X question once again.

With the likes of Voyager and Pioneer leaving the Solar System empty-handed – failing to find another planet – experts are once again becoming sceptical of the elusive planet. However, the chances of a spacecraft happening to fly past undiscovered worlds in such a vast amount of space are extremely unlikely, which means the jury is still out for Planet X until the Kuiper Cliff is finally explained.

"For many years it was thought that a world, larger than Pluto, must exist beyond it"

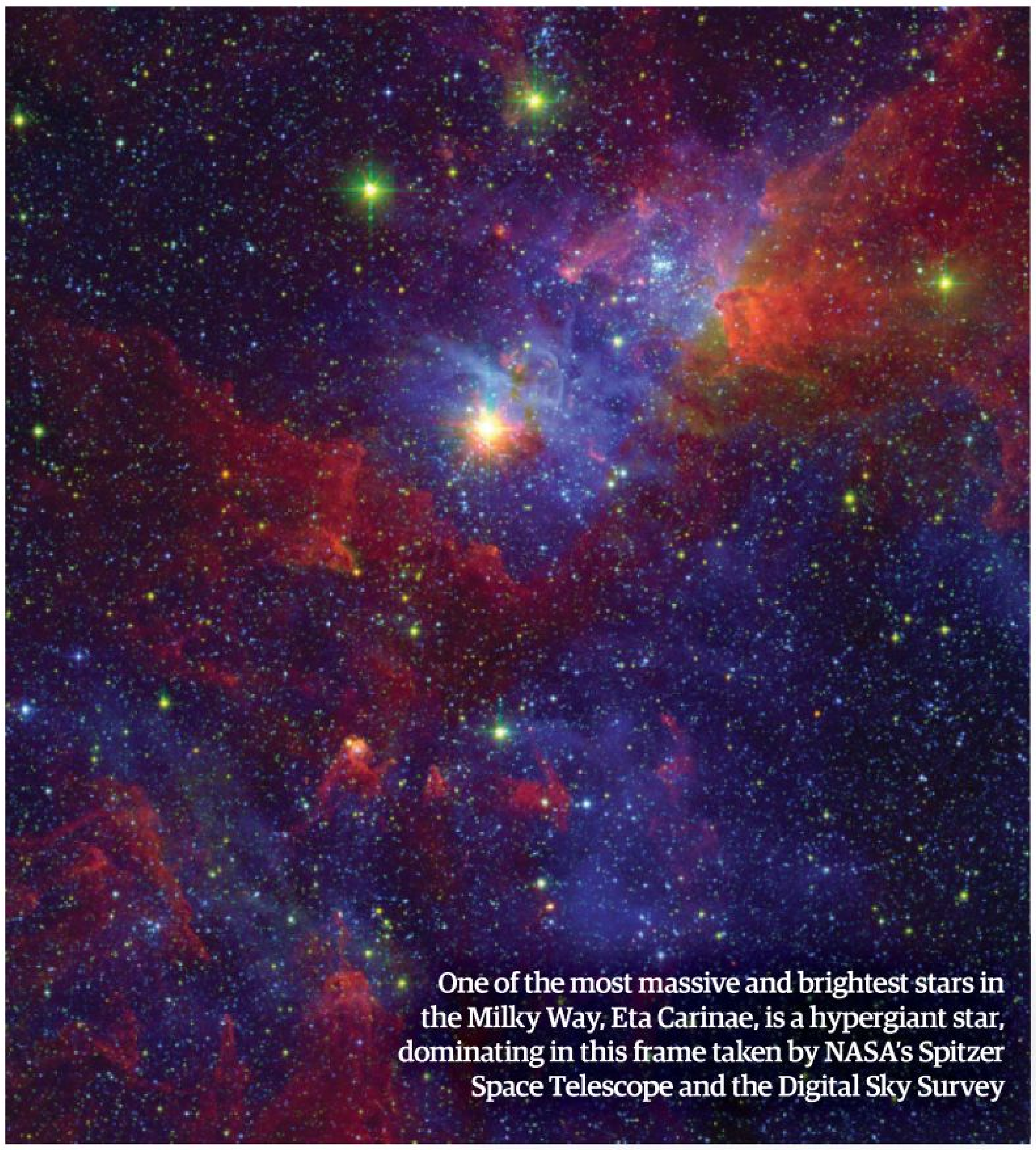
2 How do stars get so massive?

Some stars are the same size as our Sun, others are smaller, but there are some that defy all expectations. These stars are monstrously sized; with some weighing in at up to around 120-times the mass of our star.

We know that the majority of stars begin their lives in a nursery of gas and dust, located in a galaxy. When these gigantic birthing sites, or clouds, collapse, a star is born. This is also true for stars hitting around 20-times our Sun's heft, which are able to suck in the matter that surrounds them. However, as they get heavier and heavier, astronomers have been at a loss as to how they form at all.

A collapsing star of 20 solar masses or less is able to pull in a swirling accretion disk around it but anything more than this and a star will prefer to blow out radiation to such an extent it makes grabbing hold of the material to make its massive size incredibly difficult. In essence, these stars are starving themselves of the sustenance they need to continue growing. Astrophysicists are trying to put together plausible models, but there are still gaps in our knowledge when it comes to how these huge stars ever come into existence.

Observations have shown that extremely massive stars do form like stars of 20 solar masses or less, with accretion disks and matter streaming onto them in spite of their powerful radiation. One of several theories put forward is that older stars close by corral the surrounding gas with their own radiation, forcing it onto the forming giant. Another possibility is that magnetic fields in the collapsing gas cloud may be able to hold a cloud of potentially star-forming gas together until it grows so massive that it can do nothing else but collapse under its own gravity to form a monstrous star.



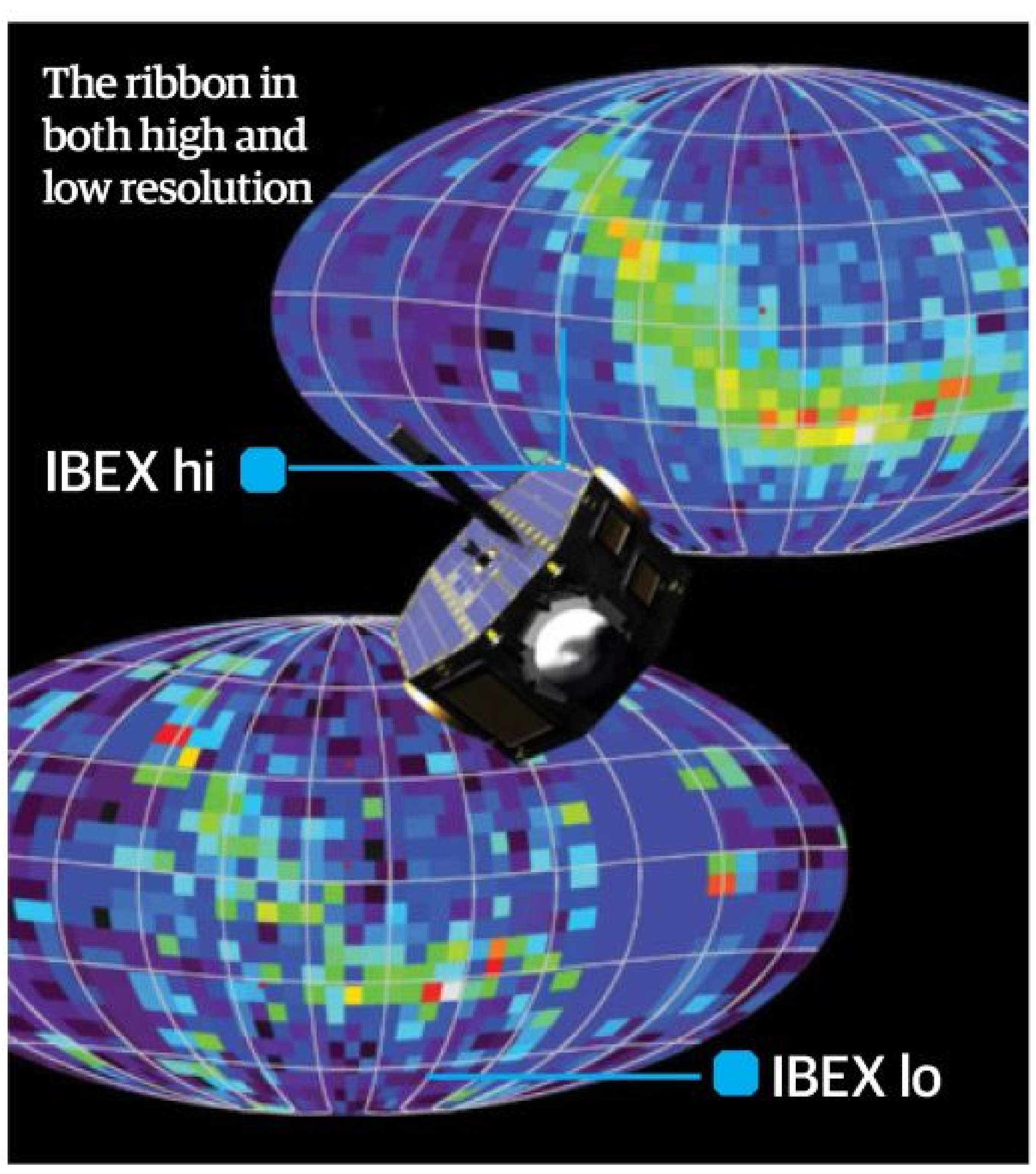
One of the most massive and brightest stars in the Milky Way, Eta Carinae, is a hypergiant star, dominating in this frame taken by NASA's Spitzer Space Telescope and the Digital Sky Survey

3 Do white holes exist?

Bring up a conversation about what lurks in our universe and black holes are likely to come up. These exotic heavyweight objects use their incredibly strong gravity to lure everything from stray chunks of gas and dust to light into their vice-like clutches. So-called white holes, however, will rarely enter anyone's minds, because, as of yet, we can't find any evidence for their existence.

As you may have guessed, white holes are the time-reversal – or opposite – of their dark counterparts, effectively separating them from their black hole cousins. Nothing can enter a white hole, but matter and light can escape it – the exact reverse of a black hole.

Technically they're not stable enough to exist but, across the board, many scientists have mixed feelings about them. Some think that they could be the end point of a wormhole – a portal – that begins at a black hole, while others have suggested that the Big Bang began as a white hole. Others still aren't too intent on finding them and think that they're entirely imaginary, simply helping us to explain current theories in general relativity, but regardless, the search for white holes will continue.



The ribbon in both high and low resolution

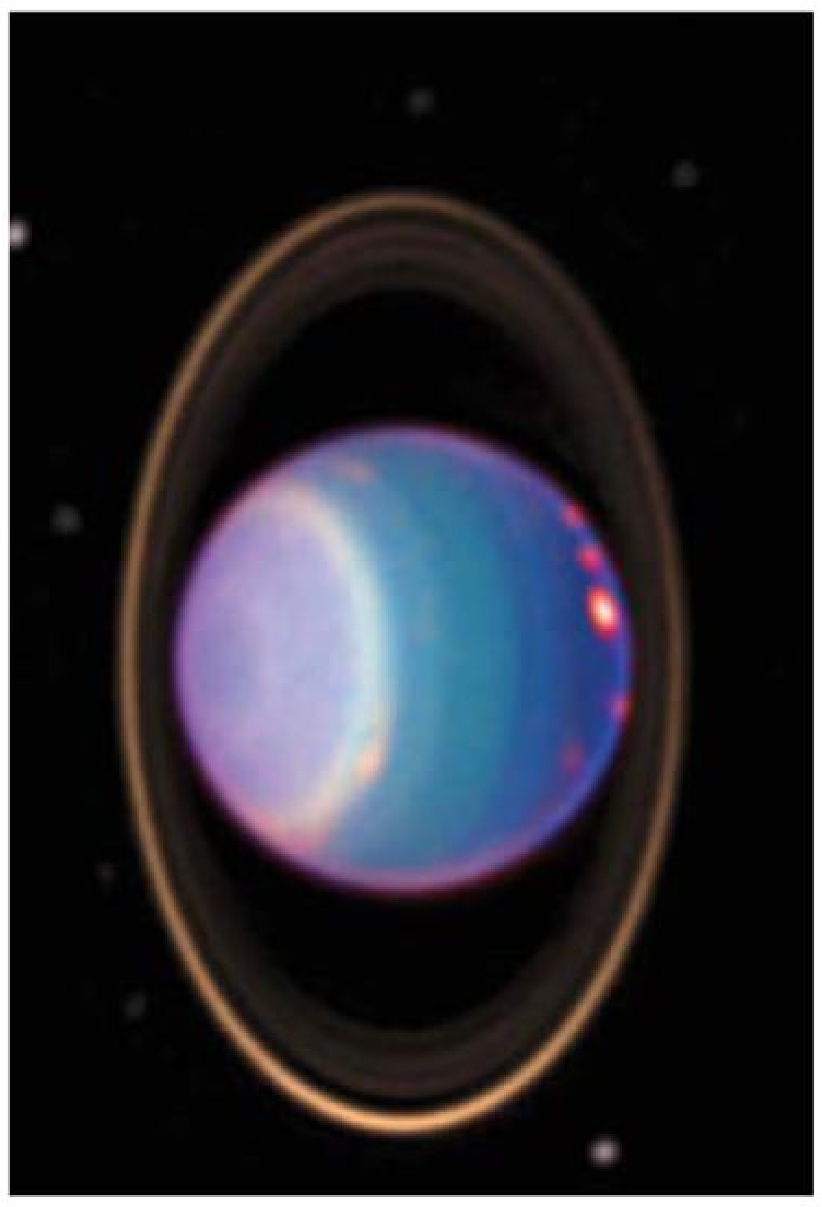
4 What is the IBEX ribbon?

When NASA's Interstellar Boundary Explorer (IBEX) satellite launched to put together a map of the gateway that separates our Solar System and interstellar space – the void where stars and their planetary systems are lacking – scientists got more than they bargained for. Surprisingly, the spacecraft found a narrow ribbon of highly energetic neutral atomic emissions.

The boundary where the Solar System meets interstellar space is invisible, emitting absolutely no light that's visible to the conventional telescope. Particles streaming from the Solar System, however, are able to bounce off the boundary, causing the neutral atoms to stream inward of their impact. With these atoms serving as fingerprints, IBEX was able to detect a vast ribbon dancing across this boundary. The evidence suggested that this ribbon was made of many more-energetic neutral atoms than the surrounding areas, but scientists have had a big task in figuring out why.

Putting together a theory hasn't been simple; earlier interpretations had to be built on and new ideas added. What's more there have been theories that directly compete with one another.

One new theory suggests that the ribbon exists in a special location where neutral hydrogen atoms of the solar wind cross the local galactic magnetic field. Here, the neutral atoms aren't affected by the magnetic fields but when their electrons are stripped away they transform into charged particles that respond to these fields and can be fired back towards the Sun. If they're able to pick off the electrons they lost at the right time – changing them to neutral – it might explain the ribbon.



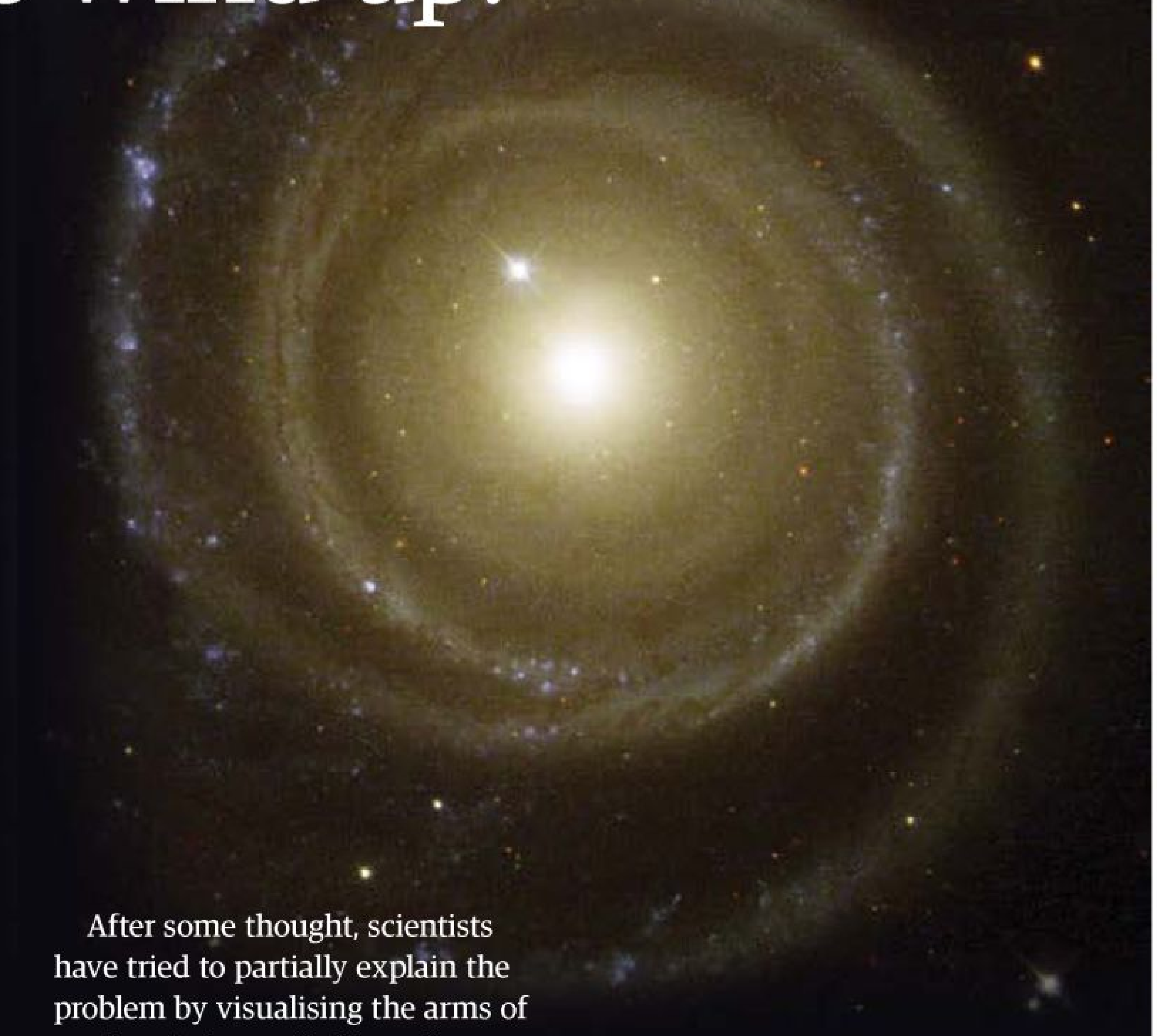
This image, taken using the Hubble Space Telescope, displays Uranus' rings. However, could Herschel have observed them as early as 1797?

5 Did Herschel see Uranus' rings?

Turning his home-made telescope to the heavens in 1781, brilliant astronomer William Herschel uncovered the seventh world from the Sun, Uranus. Originally he thought that he'd found a comet and reported it as such over a month later. However, suspicions that Herschel's finding was indeed a planet came thick and fast from astronomers as far out as Russia. Herschel had indeed found Uranus.

Herschel's records implied he had witnessed the ice giant's ring system in 1797, which should have been impossible – the rings are far too faint to be seen by amateur telescopes. It wasn't until 1977 that the rings of Uranus were discovered during an occultation, when Uranus moved in front of a star from our point of view. Uranus blocked the starlight, but scientists found that the star disappeared from view five times, pointing heavily to two rings around Uranus (subsequent observations have shown Uranus has 13 dark, faint rings).

How could Herschel have seen the rings 200 years before, given that his telescope wasn't powerful enough to see them as they are now? Had something caused them to brighten at that time, or was Herschel's observation in error? Whether he really saw the rings or not is a mystery of history.



6 Why don't galaxies wind up?

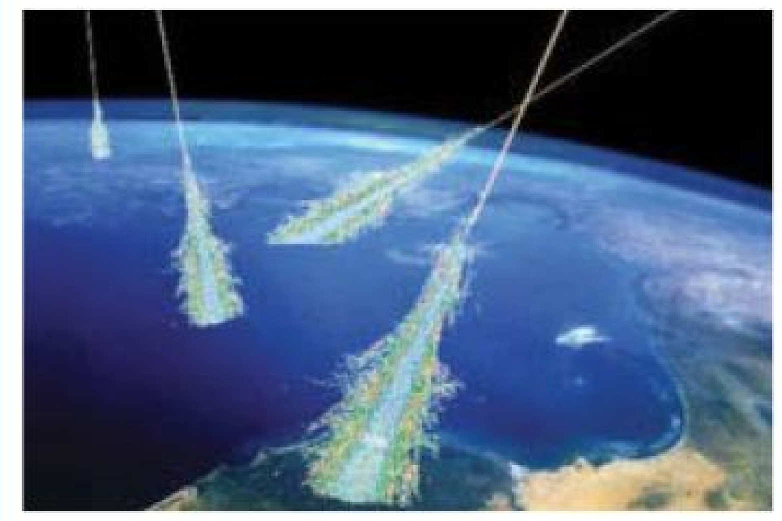
We've all wound a piece of string around our finger or needed to roll up a ball of wool after our cat has unravelled it. The key idea here is that by creating some type of rotation, we're causing this wool or string to tighten, or wind up neatly, eventually leaving you with no more yarn to wind. So, given that spiral galaxies are rotating, why isn't this happening with the arms that branch from their glowing centres? The problem we're facing is the so-called winding dilemma.

Scientists are certain that galaxies don't rotate as one – or as a rigid body – and this is what makes the way these spiral structures, spinning in the vastness of space, all the more bizarre. Experts reason that, since galaxies are moving differentially – that is, while each and every star, gas and clump of dust within a galaxy is moving at the same speed, objects further from the centre take longer to complete a lap – you would expect the parts of the arms closer to the middle to wrap around the centre faster than the outer parts, slowly winding up.

If this were the case, our universe would be littered with galaxies whose arms had tightened, just like cotton around a reel. However, even a casual glance out into the universe is enough to tell us that this isn't so.

After some thought, scientists have tried to partially explain the problem by visualising the arms of a galaxy being pulled into shape by spiral density waves. Chunks of gas and dust are squeezed by these waves, often birthing new, young stars, before moving onto the next density wave. But this still isn't the entire story and astronomers have opened up another can of worms by questioning the origin of the waves in this theory. Where did they come from? Right now, your guess is nearly as good as theirs.

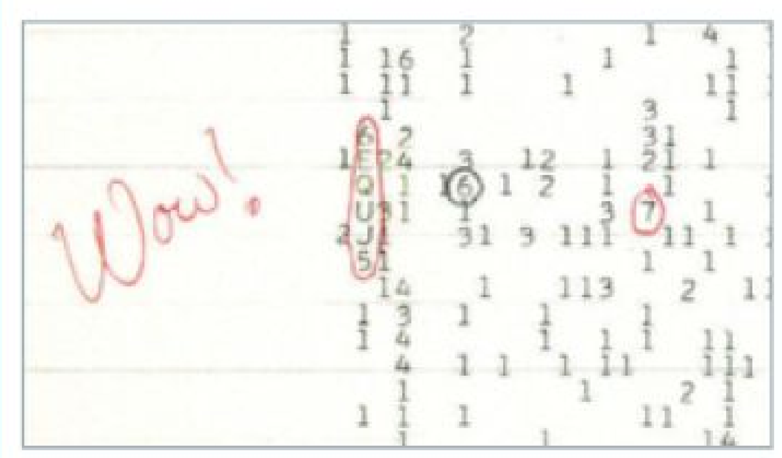
> "Just why isn't this happening with the galaxies' arms?"



7 What is the OMG particle?

An ultra-high-energy cosmic ray became known as the OMG particle when it streaked close to the speed of light into the path of the University of Utah's Fly's Eye Cosmic Ray Detector. Astrophysicists couldn't explain this cosmic ray of energy comparable to 40 million-times that of the highest energy particles that have ever been made.

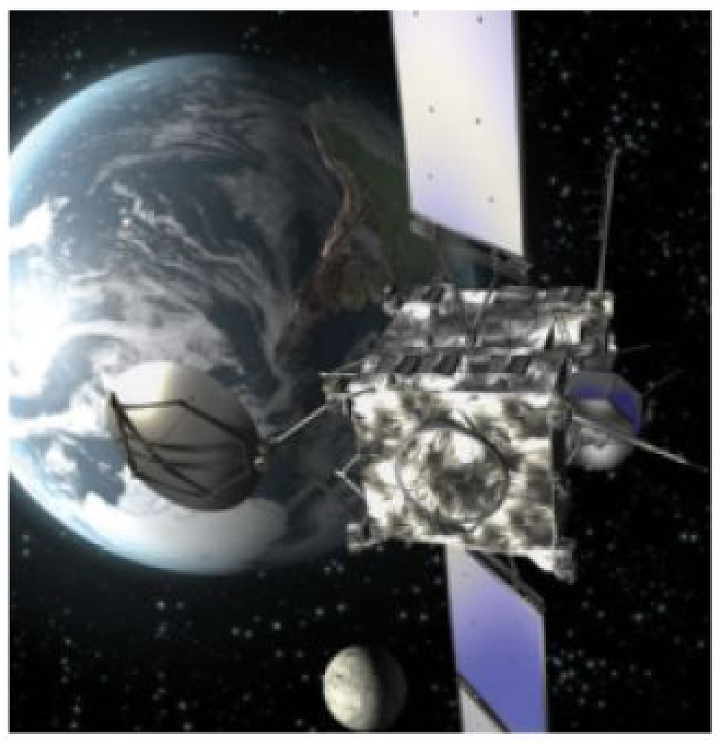
Experts think that the cosmic ray takes the form of a rare high-energy proton. The phenomena has been witnessed 15 times and its energy is about 20 million-times more powerful than radiation spewed by extragalactic objects.



8 What happened to the Wow! signal?

Detected by astronomer Jerry Ehman in 1977, as part of a project involving the Search for Extraterrestrial Intelligence (SETI), the Wow! signal was a strong radio burst that got its name after Ehman wrote 'Wow!' on the print-out from the observatory computer that recorded the signal.

Relating it to a signal that we'd expect from interstellar space, Ehman and others attempted to find the 72-second signal, but it never resurfaced. Was it a message from aliens, a radio echo from a terrestrial source or an unidentified phenomena?



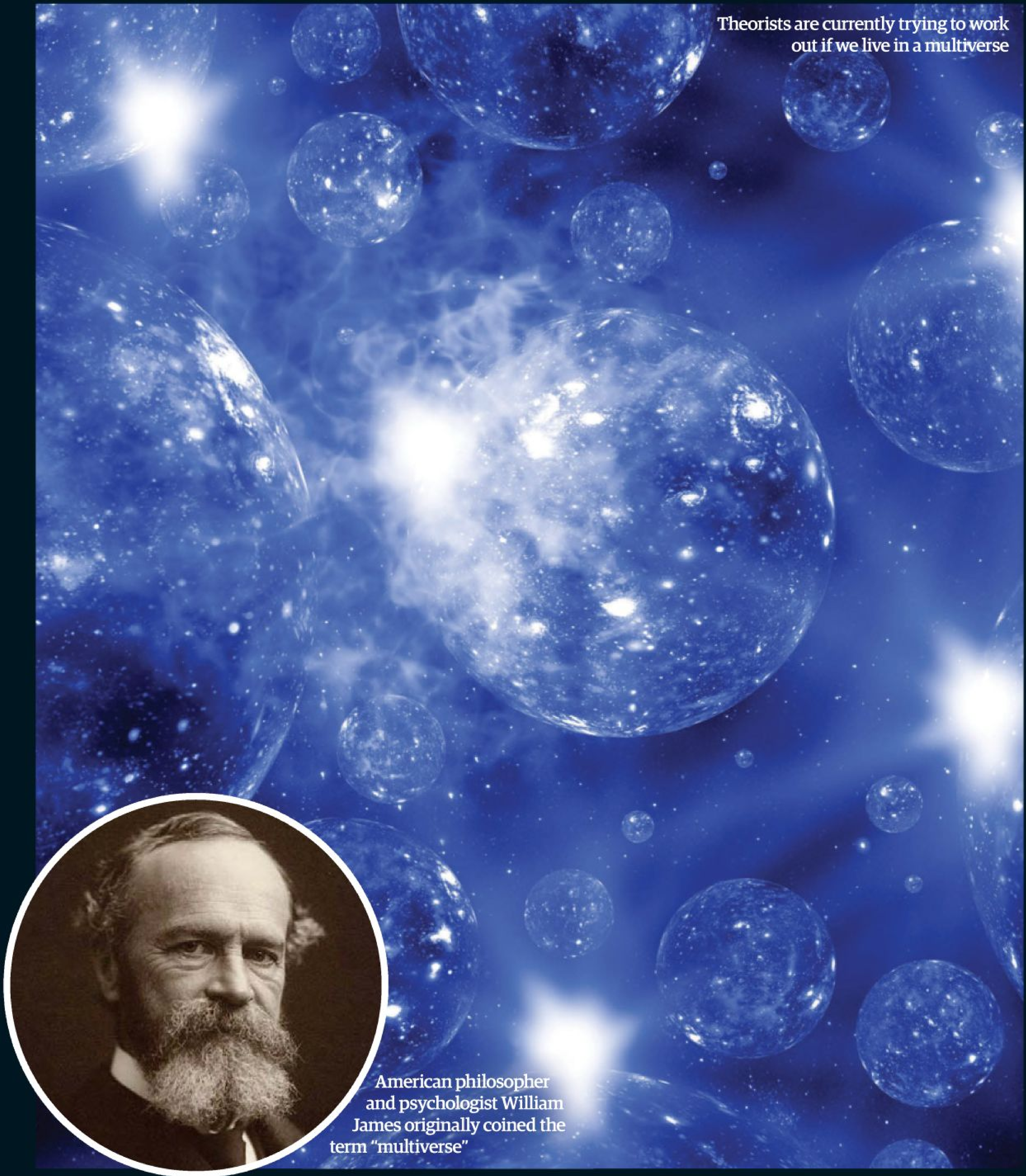
ESA's Rosetta spacecraft gets a buzz of energy from our planet

9 Why do spacecraft speed up near Earth?

When spacecraft pass the Earth, they get a buzz from it and this sudden boost makes them speed up, but what's causing it? Nobody really knows the answer. Even researchers at NASA's Jet Propulsion Laboratory have thrown up their hands, hoping that the world's physicists would come up with an answer. That solution doesn't seem to have arrived yet, although we've come to expect what we refer to as the flyby anomaly.

It first happened when the Jupiter-bound Galileo spacecraft broke into a sprint when it swung by our planet in 1990 and 1992, followed by NEAR in early 1998 and then Cassini in 1999, while the Rosetta spacecraft also experienced the same boost.

The most obvious boost in speed, which changed a good 13 millimetres per second more, was recorded for the Near Earth Asteroid Rendezvous – Shoemaker (NEAR Shoemaker) spacecraft. Scientists figured that the anomaly was much too big to be explained by Einstein's general theory of relativity. However, arming themselves with a variety of suggestions, some experts think that they might have the answer, suggesting that the anomaly could be due to the Earth's spin on its axis. There could also be some type of dark matter halo around our planet. The possibilities keep coming, but the answer that fully fits the problem is as yet still unknown.



Theorists are currently trying to work out if we live in a multiverse

American philosopher and psychologist William James originally coined the term "multiverse"

10 Do we live in a multiverse?

Just when we thought the universe was complicated enough as a single entity, along comes the suggestion of a multiverse; the possibility of more than one universe connected to our own. These universes could hold some of the mysteries of our immediate cosmos, directly multiplying its complexity many times over.

The idea of alternative, or parallel, universes has come under fire with cosmologists regarding the theory as loosely scientific, querying how the idea of a multiverse could be tested, exactly. Others suggest that to even consider what they regard as unobservable universes aggravates Occam's Razor – the notion that among competing suggestions, it's the idea with the fewest assumptions that should reign triumphant. In short, you would need to assume a lot for a multiverse to be feasible.

However, not everyone has blasted the idea, with some taking the concept as a cue to investigate its validity. Experts are scanning the cosmic microwave background radiation – the relic emission that crackled behind the contents of the universe when it was breathed into life – for disk-like structures that could point out collisions between our universe and others. Results brought to the table by ESA's now defunct Planck space observatory have pointed to these cosmic bruises and present the idea that our universe crashed into the others at least four times during its long history.

However, until more evidence is found, the concept of us in our historical universe being repeated many times over in many other universes will have to wait.

Organisms that thrive in extreme conditions could exist on other planets. They provide bright colours here on Earth, as shown at Grand Prismatic Spring, Yellowstone National Park

11 Is there extraterrestrial life?

This question must be the most-often asked when we think about the expanse of the cosmos. If Earth has the right conditions to support life, then surely there must be the perfect environment for life to exist elsewhere, not just in our galaxy but beyond its confines. We are clearly interested in looking for life as we know it, but when they talk about life in the universe, astronomers warn us not to limit ourselves. Microbes and bacteria that survive quite happily in the most extreme environments – whether they're sweating it out on a very heated world or shivering in a freezing-cold climate – are also classed as life.

This, you'd rightly think, makes it more feasible that there's life out there. However, since we have no concrete evidence that other beings – as or more intelligent as us – have attempted to communicate with Earth, expecting extremely simple microbes to let us know they're living on a distant exoplanet sounds very far-fetched.

This is why we use Earth as a template when trying to figure out if there's life on other worlds. Lake Vostok in Antarctica easily passes for the freezing conditions on Jupiter's moon Europa and the hot springs at the USA's Yellowstone National Park could represent an extremely heated environment – these are the keys in helping us to figure out how microbial life forms tick. Not only that, but we also look for signatures of molecules that tell us someone's at home – methane, oxygen and water being the favourites. Several exoplanets have revealed these tell-tale signs along with being at a favourable distance from their star to support liquid water but, without an advancement in our technology and the launch of devices such as the James Webb Space Telescope, we are unable to lock down that life exists for sure – at least for now.

12 Why do Venus and Uranus have odd spins?

Great collisions in Venus and Uranus' history could have given them their unusual rotations

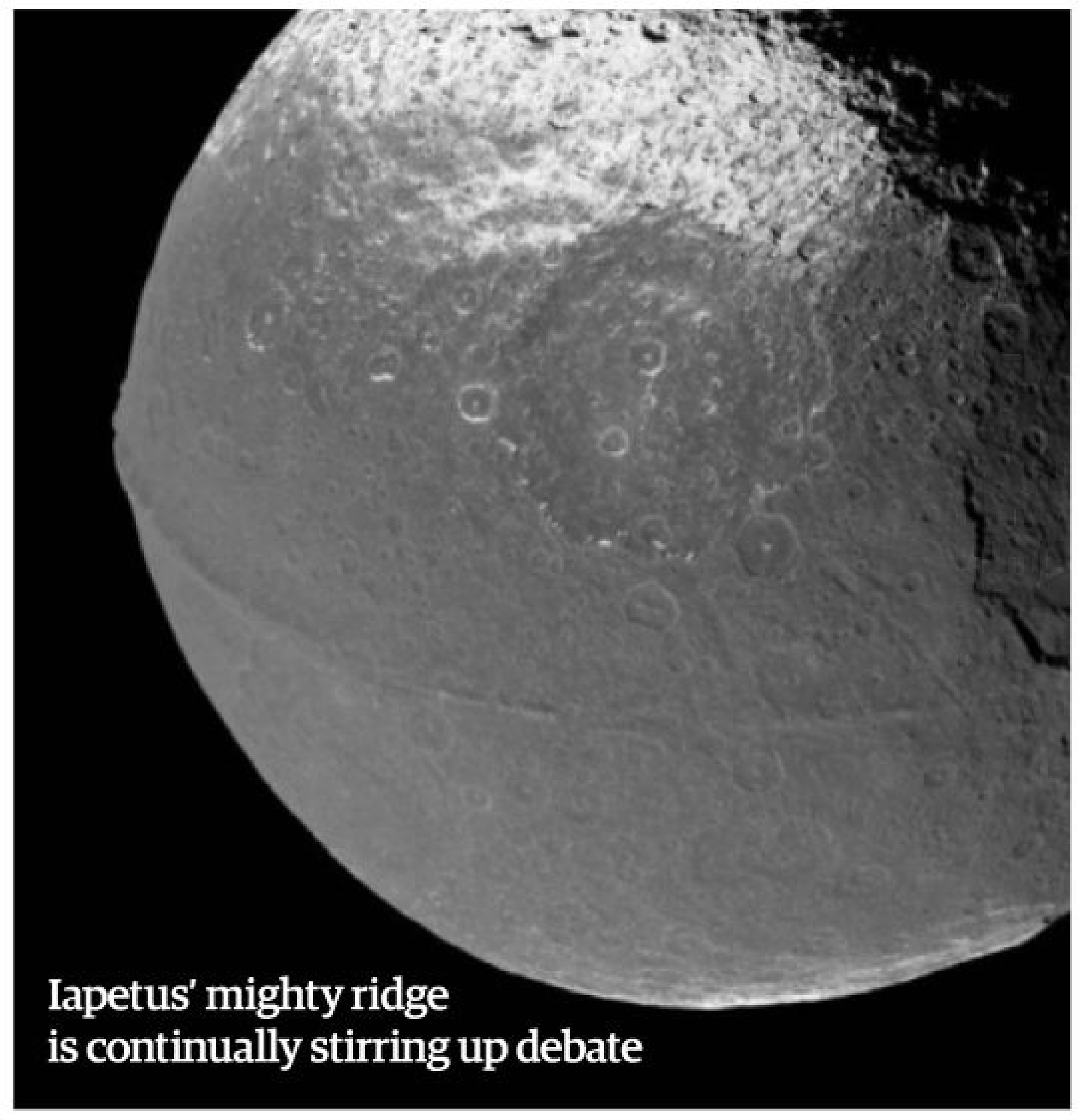
Grab a bird's eye view of our Solar System and not only will you get an appreciation for its sheer size, but you'll also notice that there are a couple of celestial odd balls.

When the Solar System was made from the swirling pancake of gas and dust that would later clump together to make the planets, this industrious construction yard in space threw the planets on a counterclockwise orbit and axial spin. Venus might follow suit in its orbit, but its rotation is opposite to the other planets.

Further out rests Uranus, which probably collided with another body in the early Solar System, causing it to roll, rather than spin, around the Sun.

So what happened to these two worlds to set them apart? There are several theories, but the most widely accepted is that some dramatic event occurred while the planets were being formed. In the case of Venus, it's possible that it absorbed another body, causing it to have more mass, resulting in a greater speed and an altered rotation. The same could have happened to Uranus, whose moons could have resulted from matter being dredged up and flung into orbit around the developing gas giant.

13 Why is Iapetus walnut-shaped?



Iapetus' mighty ridge is continually stirring up debate

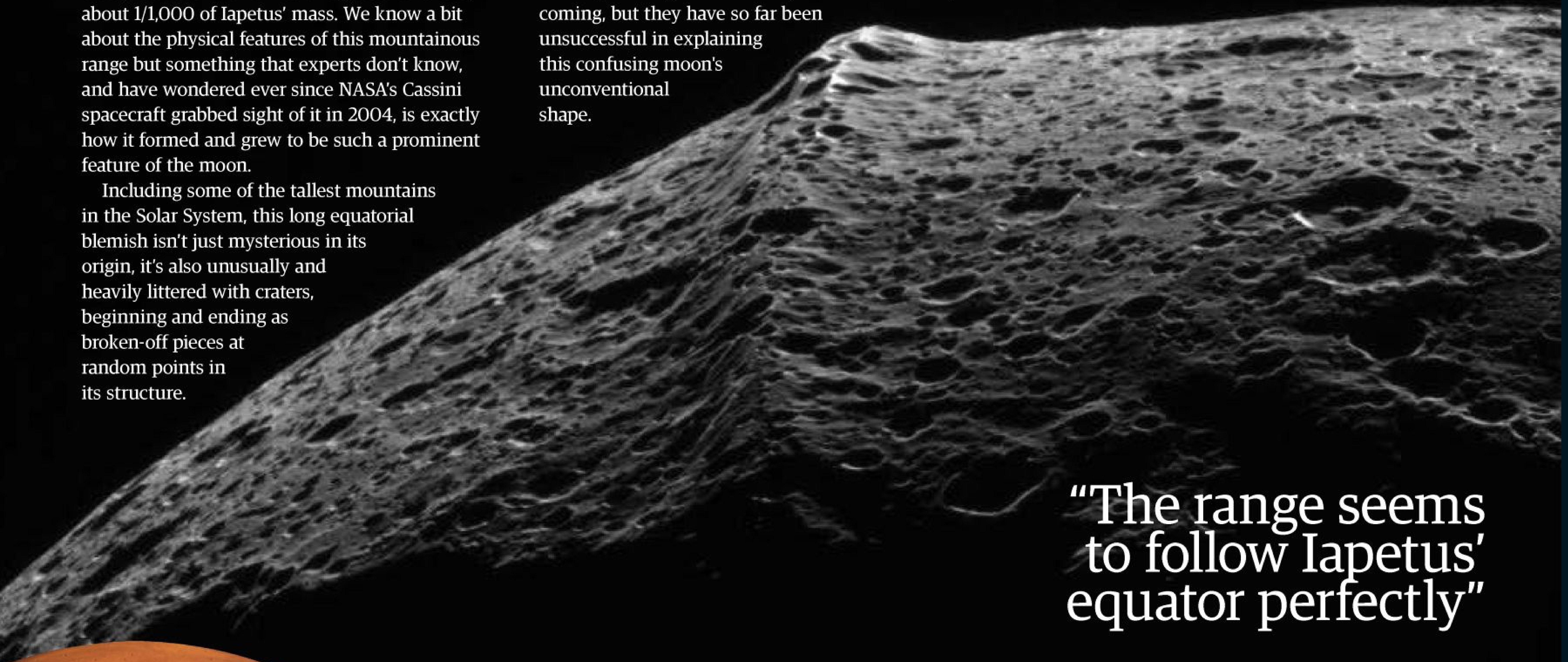
Take a look at Saturn's third-largest moon, Iapetus, and the first thing you'll probably notice is that the ringed planet's satellite has a ridge that makes it look like an oversized walnut.

This bizarre appearance is caused by the mountainous range that wraps around its equator. This ridge is like no other in the Solar System; it rises from the icy surface, reaching up to 20 kilometres (12.4 miles) high and pans out to be 200 kilometres (124 miles) wide. It's also thought that this enormous ridge could take up about 1/1,000 of Iapetus' mass. We know a bit about the physical features of this mountainous range but something that experts don't know, and have wondered ever since NASA's Cassini spacecraft grabbed sight of it in 2004, is exactly how it formed and grew to be such a prominent feature of the moon.

Including some of the tallest mountains in the Solar System, this long equatorial blemish isn't just mysterious in its origin, it's also unusually and heavily littered with craters, beginning and ending as broken-off pieces at random points in its structure.

However, despite being quite isolated in places, the range seems to follow Iapetus' equator almost perfectly. This makes the puzzle even more intriguing, especially since it mainly lies in the dark Cassini Regio region.

Scientists behind Cassini have made some suggestions: did Saturn's minion become squashed down thanks to rapid rotation in its younger days? Did it once have a ring system during its formation that eventually collapsed onto the moon's surface, creating the ridge we see today? The theories keep coming, but they have so far been unsuccessful in explaining this confusing moon's unconventional shape.



"The range seems to follow Iapetus' equator perfectly"

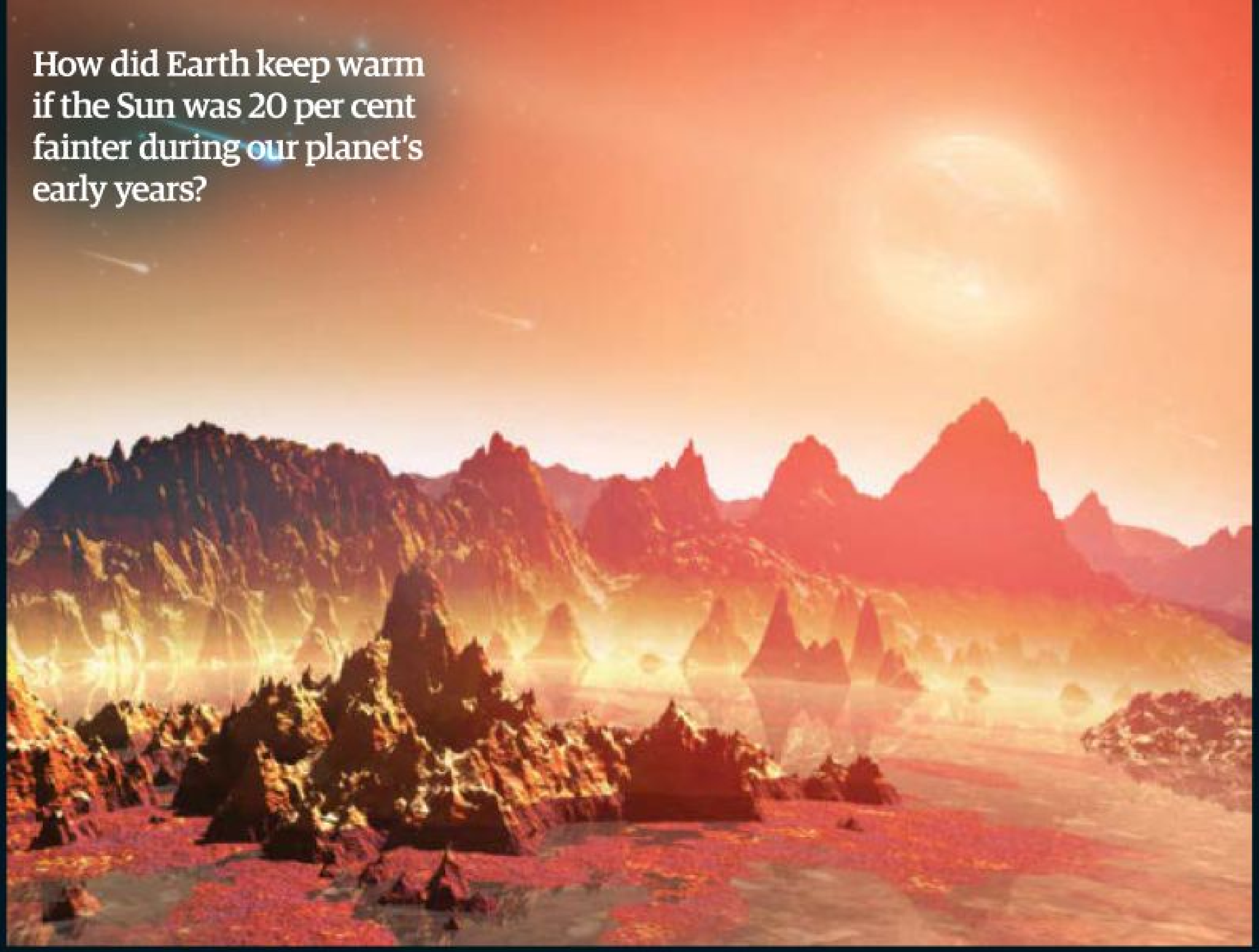
14 Was there life on Mars?

Trundling along the surface of the Red Planet, occasionally stopping to sample and probe the Martian soil, the rovers Opportunity and Curiosity are busy at work trying to discover, among other things, if Mars was once ever capable of supporting life on its stretches of solar wind-stricken land.

Many a mission has brought us snippets of information that would remain otherwise unknown about the Red Planet if we hadn't sent these scouts to the surface to search for clues. It's been hinted that Mars might have been very much like Earth in its earlier years. When the planet lost its magnetic field, Mars began to degrade, becoming awash with stronger radiation after losing its atmosphere to the solar wind. This left the barren, possibly lifeless world as our next-door neighbour.

In 2013 Curiosity's inboard instruments hit upon something - the key ingredients for life including oxygen, nitrogen as well as clay minerals that suggest a lake or ancient streambed that could have existed long ago and was neither neutral or too salty. Evidence for an Earth-like world was further hardened when the rover found signs of an ancient freshwater lake that could have been the home of simple lifeforms such as bacteria. The flowing of liquid water on the surface of Mars suggests that a magnetic field once shielded it from radiation.

Clearly this doesn't suggest that life ever inhabited Mars and until we find further evidence of it, the question of whether life lived happily on the ruddy soil still remains.



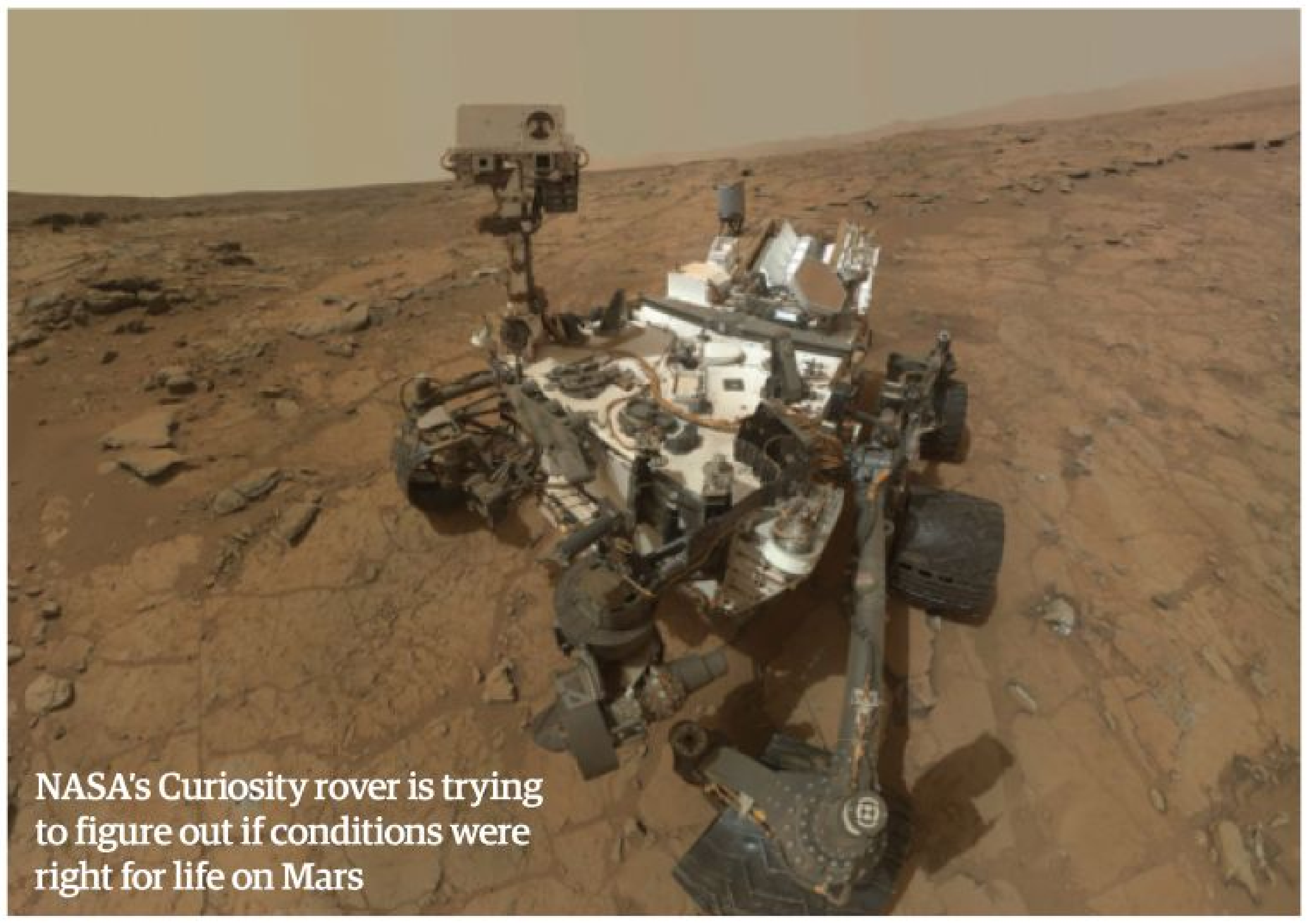
How did Earth keep warm if the Sun was 20 per cent fainter during our planet's early years?

15 How did liquid water exist on the young Earth?

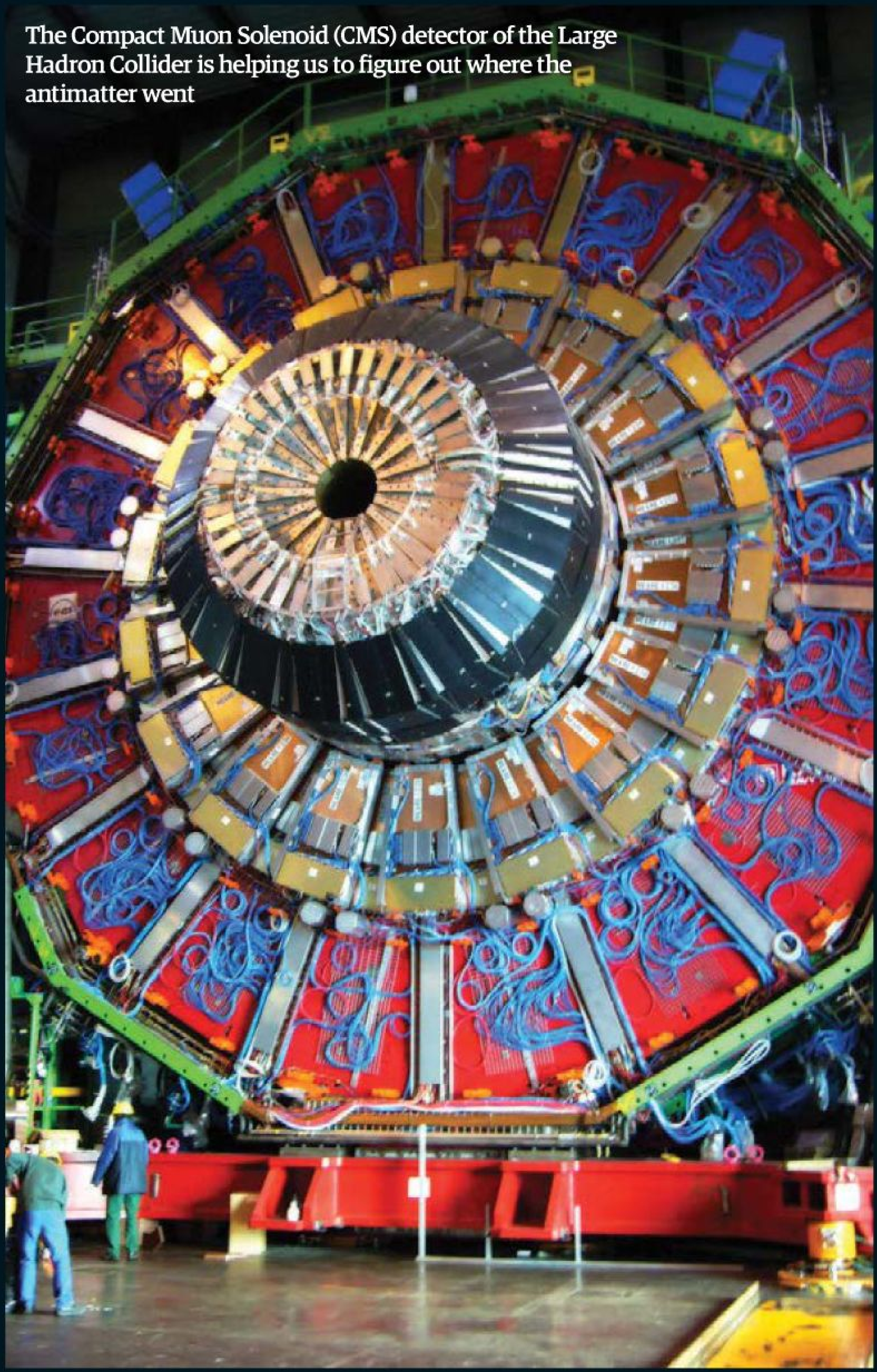
When our planet was young, it would have been showered with light that was only 70 per cent the intensity that our Sun emits now. What this means is that the Sun was quite faint and, according to astronomers such as Carl Sagan and George Mullen in 1972, it wouldn't have been able to support water in a liquid consistency, but more of a frozen one. This is what astronomers refer to as the Faint Young Sun paradox.

Teams of scientists from all over the world have traced back into the Earth's early years and suggested that its atmosphere could have harboured more greenhouse gases. Choking carbon dioxide might have been higher as well as the pressure by about ten times. Methane might well have also been extremely prevalent, actively driving the greenhouse effect and reacting with oxygen to manufacture even more carbon dioxide along with water vapour.

Other researchers have since come forward stating that a high pressure along with carbon dioxide might well have been high enough to stop our young planet from freezing over. Others have suggested a cycle that could have stopped to bring ice age periods and start back up again thanks to the eruptions of volcanoes spewing out carbon that warmed the atmosphere in a greenhouse effect.



NASA's Curiosity rover is trying to figure out if conditions were right for life on Mars



The Compact Muon Solenoid (CMS) detector of the Large Hadron Collider is helping us to figure out where the antimatter went

16 Where did the antimatter go?

The unequal amount of antimatter to matter ratio in the universe might be one of the top mysteries of the cosmos, but without there being more matter than antimatter, there would be no galaxies, no stars, no planets and certainly no us.

The Big Bang was supposed to make equal amounts of matter and antimatter. Antimatter is the equal, yet opposite material to matter and when they meet, they annihilate to produce radiation. This is where things take an unexpected turn – if there were equal amounts of matter and antimatter and they annihilated, then there would be nothing but radiation filling the universe. One look around us tells us they clearly weren't in equal quantities, so why are we left with a surplus of matter?

Theorists have come up with two plausible solutions. One explanation – according to the likes of the people behind the Large Hadron Collider at CERN – showed that one particularly exotic particle known as the Kaon morphed into its antiparticle more often than the reverse happened. A tiny imbalance between matter and antimatter would have been evident.

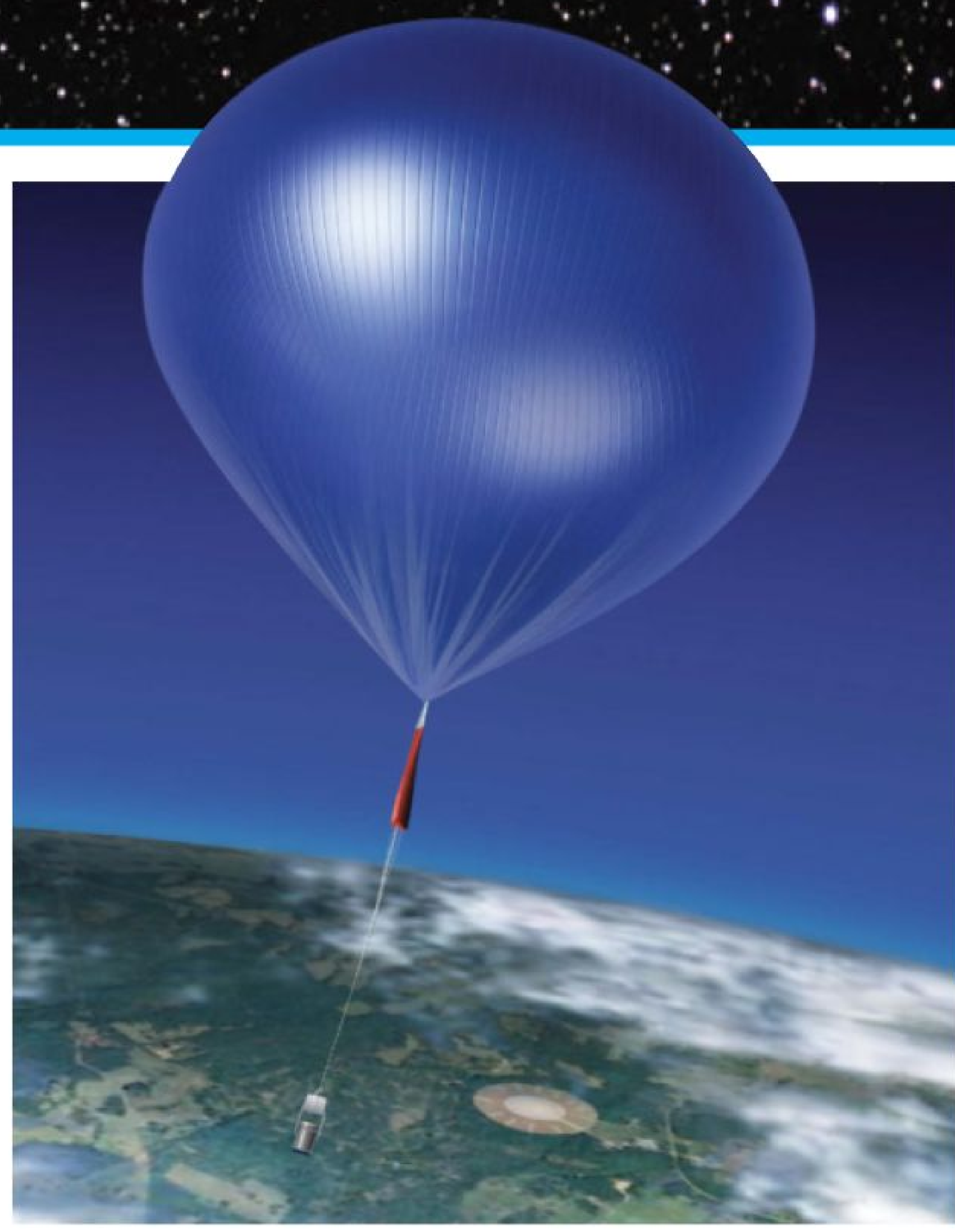
The second is that it might have been plausible the two populations of opposite particles avoided their fatal grasp – could there be anti-galaxies, anti-stars and even anti-life out there making a mirror image of our universe and the objects in it?

18 Why are there fewer heavy elements?

Popular theory shows that the cosmos wasn't supposed to have been sparing with the elements heavier than hydrogen and helium - in particular lithium-7 - that were meant to have been made after the Big Bang. It's not just a small amount of these heavier elements that scientists think is missing, but quite a huge chunk. This is according to studies that take a closer look at old stars that populate the outskirts of the Milky Way.

But the Small Magellanic Cloud, a tiny galaxy near our own, has the right amount today that the Big Bang predicts, which scientists thinking must have started its life with less lithium than it should have.

"What it got was a gigantic boom about six times stronger than it predicted"



17 Why is the cosmos six-times louder?

The cosmos sometimes has bursts of sound through the medium of radio waves first picked up by the Absolute Radiometer for Cosmology, Astrophysics and Diffuse Emission. The NASA-built receiver attached to a balloon was released to the skies on the hunt for radio signals from stars and galaxies. What it got was a gigantic boom about six-times stronger than predicted.

This is too loud to belong to the stars and galaxies, a squeak in comparison, and it's interfering with our view of the universe.

19 What cleared the universe fog?

Around 13 billion years ago every corner of the early universe was swathed in a thick hydrogen fog, immediately after a time where there was so little light because the fog completely blocked out any available light from the very first stars.

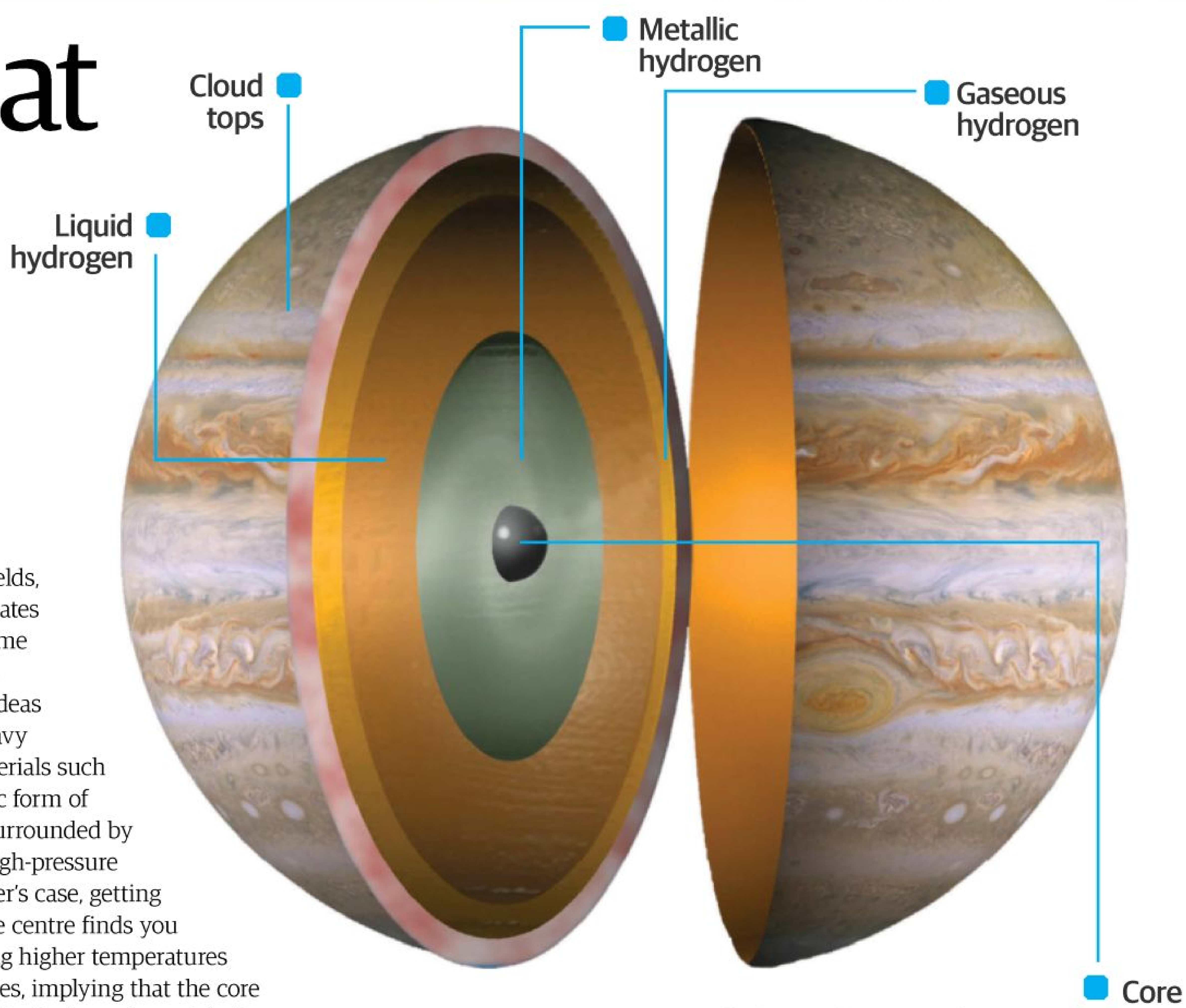
This fog enabled the makings of not just stars, but galaxies and black holes. The idea is that something began to burn off the cosmic mist in what is known as reionisation, where protons and electrons became so cool that they were attracted to one another, pulling themselves into atoms of hydrogen and suddenly photons could travel freely through the universe. A few hundred million years later, atoms were stripped of their electrons and forced apart by the cosmos' expansion, preventing them from recombining and causing the fog to disappear. It's thought that ultraviolet light thrown out by the first stars could possibly be the culprit, but were enough stars being created at the time? Was the light from active black holes to blame?

Combine this question with the fact that our telescopes are pushing to the limits of how far back they can look and the mystery thickens. Some astronomers have attempted to find a way around the distance issue by observing galaxies where reionisation has just finished on their outskirts. New discoveries are revealing a population of faint, small galaxies that are 100-times more common than the larger galaxies and these could have provided the stars and radiation necessary to reionise the universe.

20 What's at the centre of the gas giants?

When we think of the gas giants, some often imagine them as great spheres of gas and ice through and through, with no solid ground for missions to land but to instead become squashed under the intense gaseous pressures of their atmospheres. According to current theories, however, it's thought that these gaseous limbs of the planets must be wrapped around some core, but what this core is made of is a bit of a puzzle. With missions unable to find out for us, as they'd likely perish in the planet's unforgivable atmosphere, we can only really look to our models and the fact that the outer planets generate magnetic fields, which indicates a core of some description.

Current ideas point to heavy molten materials such as a metallic form of hydrogen surrounded by a layer of high-pressure ice. In Jupiter's case, getting closer to the centre finds you experiencing higher temperatures and pressures, implying that the core must be quite slushy and consist of both liquid and solid.



Scientists are unsure of what's at the centre of gas giants like Jupiter. Some believe that its core is dense with a mixture of elements.

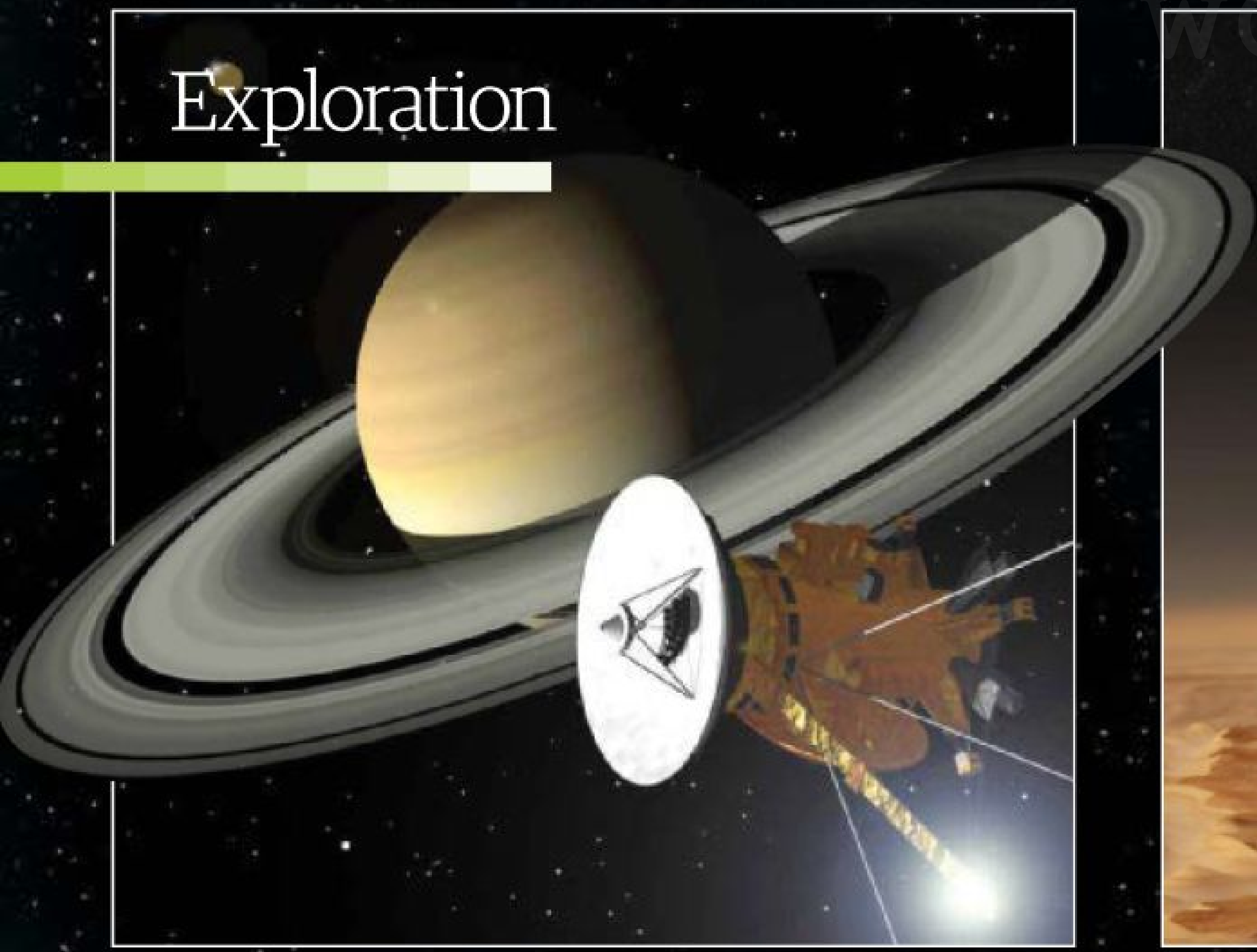
Exploration

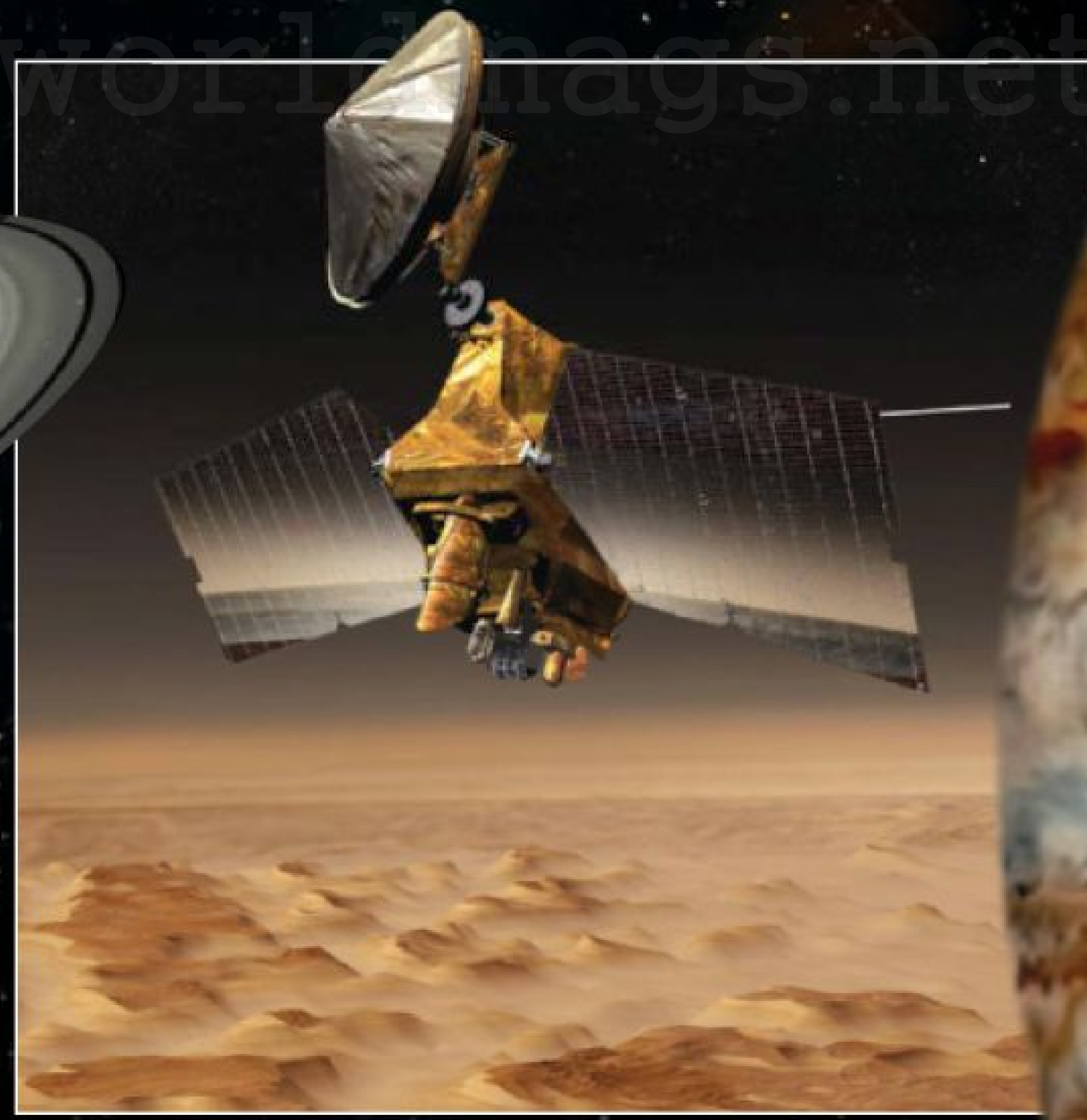
Missions to the planets, our cosmic back yard and beyond

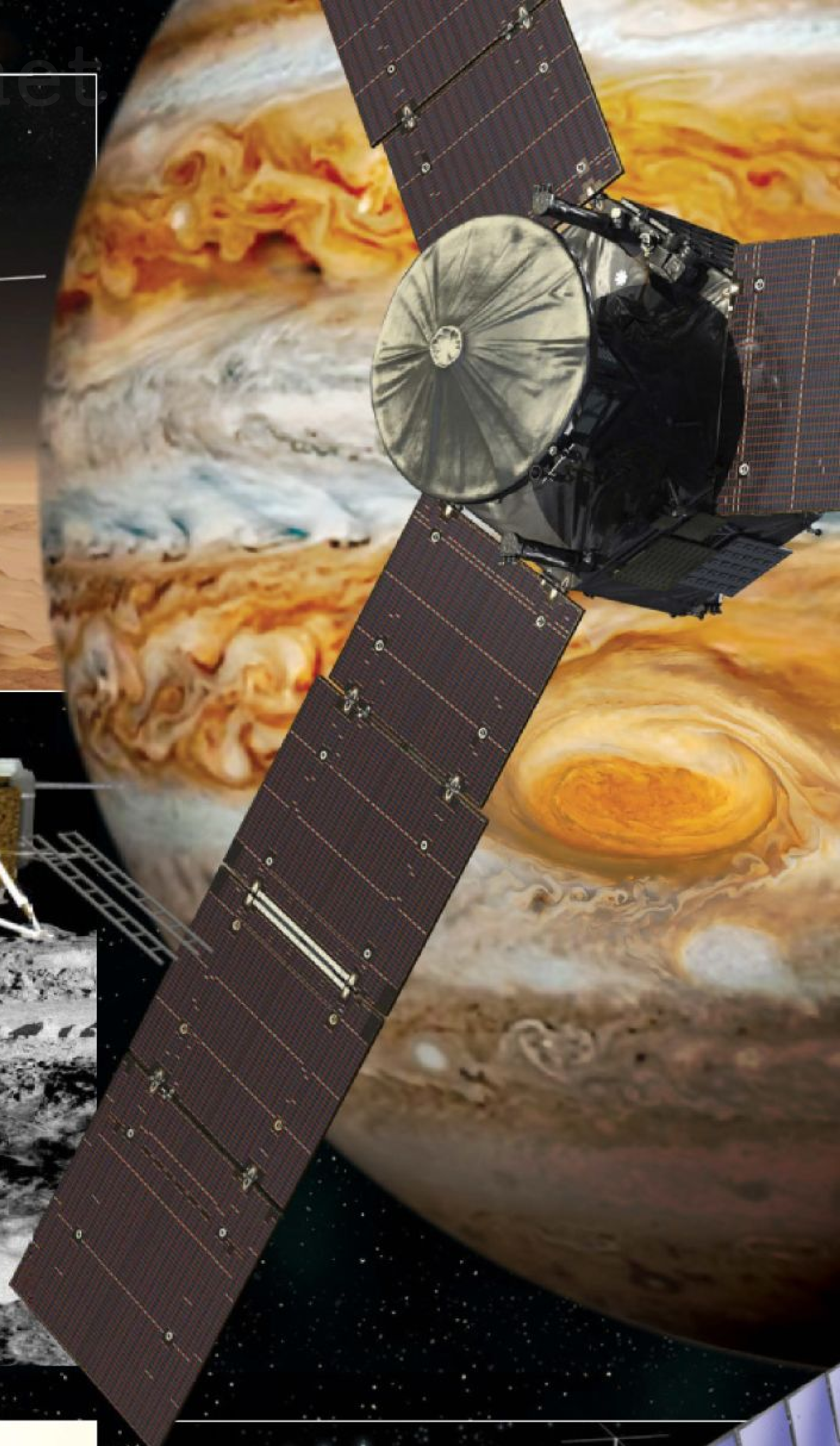
"The Milky Way is pocked with bubble-like cavities created by massive stars"

50
Explore the Milky Way

©NASA, Boeing, Adrian Chestermann

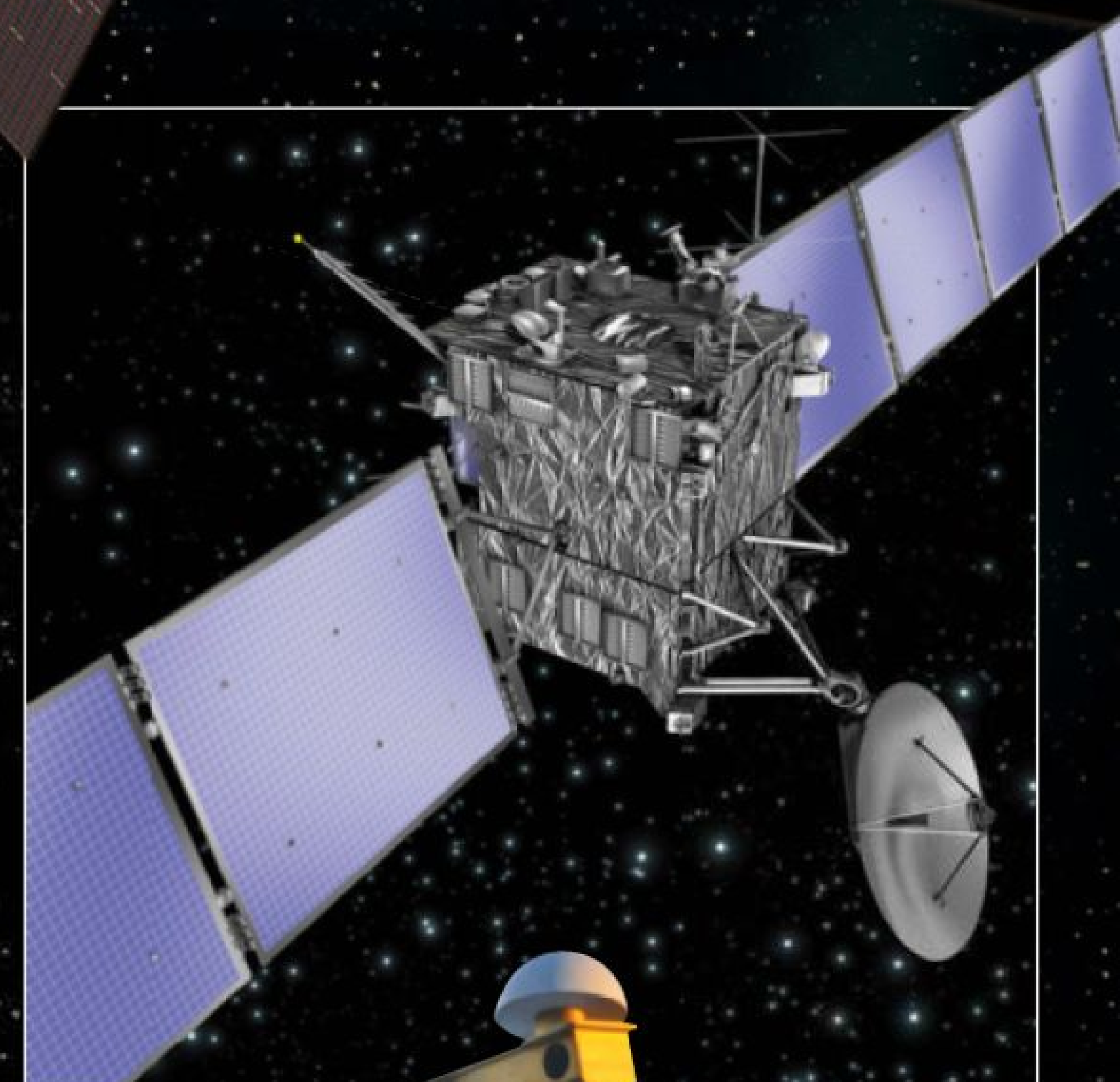


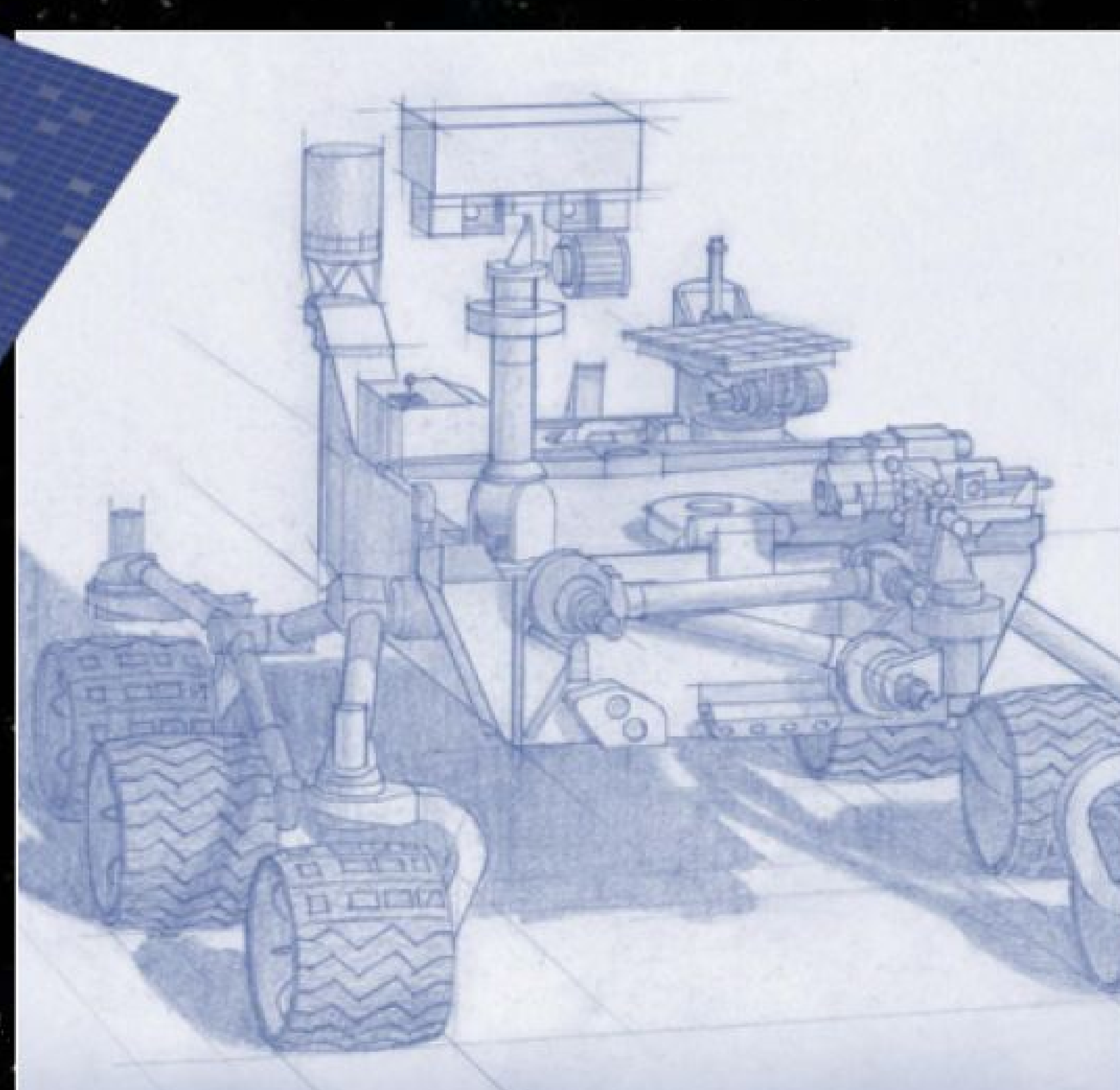





SPACEX


Inspiration MARS






Google
LUNAR XPRIZE

20 INCREDIBLE SPACE MISSIONS

From drilling on Mars to deflecting asteroids, we take a look at the most exciting, dangerous and ambitious missions of the present and future

The foremost space programmes of the world will reach their first centenary by the mid-point of this century. A hundred years is enough to see many industries achieve a degree of maturity but for space, we'll have barely made it out of the cradle and be crawling on all fours. NASA might have achieved a lunar landing within a decade of being established but after 60 years of exponential growth in the space industry, the collective efforts of humankind has seen no more than a few dozen landers and orbiters in Earth's planetary neighbourhood and a handful of probes venturing beyond the asteroid belt. As yet, we haven't set foot on another planet, we haven't even been back to the Moon since the last Apollo mission 40 years ago, and still only a privileged few will have escaped Earth's atmosphere within the next few generations to experience the weightlessness of space beyond the Kármán line.

Not that we're disparaging the enormous achievements scientists have made in the name of astronomical pursuits but, despite being an industry at the bleeding edge of every science, exploration beyond our terrestrial sphere is limited by the extremes of the cosmos. That's what makes it so fascinating, even to watch it unfold as a casual observer: the first people and machines to photograph distant worlds or poke beneath the crusts of moons is the stuff that has fuelled science fiction for generations. With space no longer the exclusive domain of the government agencies, whether you're a NASA project scientist or an amateur stargazer, the next year, decade and beyond is going to be an incredible time for all.

1. Orbital mechanic

Russia has grand plans for its new space station

Name: OPSEK | **Launch date:** 2020 | **Mission:** Space station

In 2020 or possibly as late as 2028, depending on whether further funding can be secured, the International Space Station will be decommissioned. Its end-of-life plan is likely to start with its deconstruction, followed by a deorbit of its modules and a destructive re-entry over a safe terrestrial corridor.

The Russian Federal Space Agency, however, has plans for a second life for the Russian orbital segment of the ISS. It will use some of its modules, possibly the Zvezda service module and mini research module Poisk, to form the basis of a new space station called OPSEK, the Orbital Piloted Assembly and Experiment Complex. In the wake of nearly a dozen other Russian space stations, it will be the most advanced of its kind, a third-generation modular station that will serve as an orbital platform. As a stop-off point for spacecraft that will go on to outer space missions to the rest of the Solar System, OPSEK will be involved in maintenance, repairs, test flights and provide medical facilities for crew rehabilitation. Its most interesting function, though, will be in creating and servicing space tugs used to tow craft to and from orbit as well as the assembly of larger spacecraft brought to the station in pieces. As a modular station, OPSEK's components can be removed or more added according to its needs. This means it could grow to be bigger and provide a more important role in space exploration than the ISS.

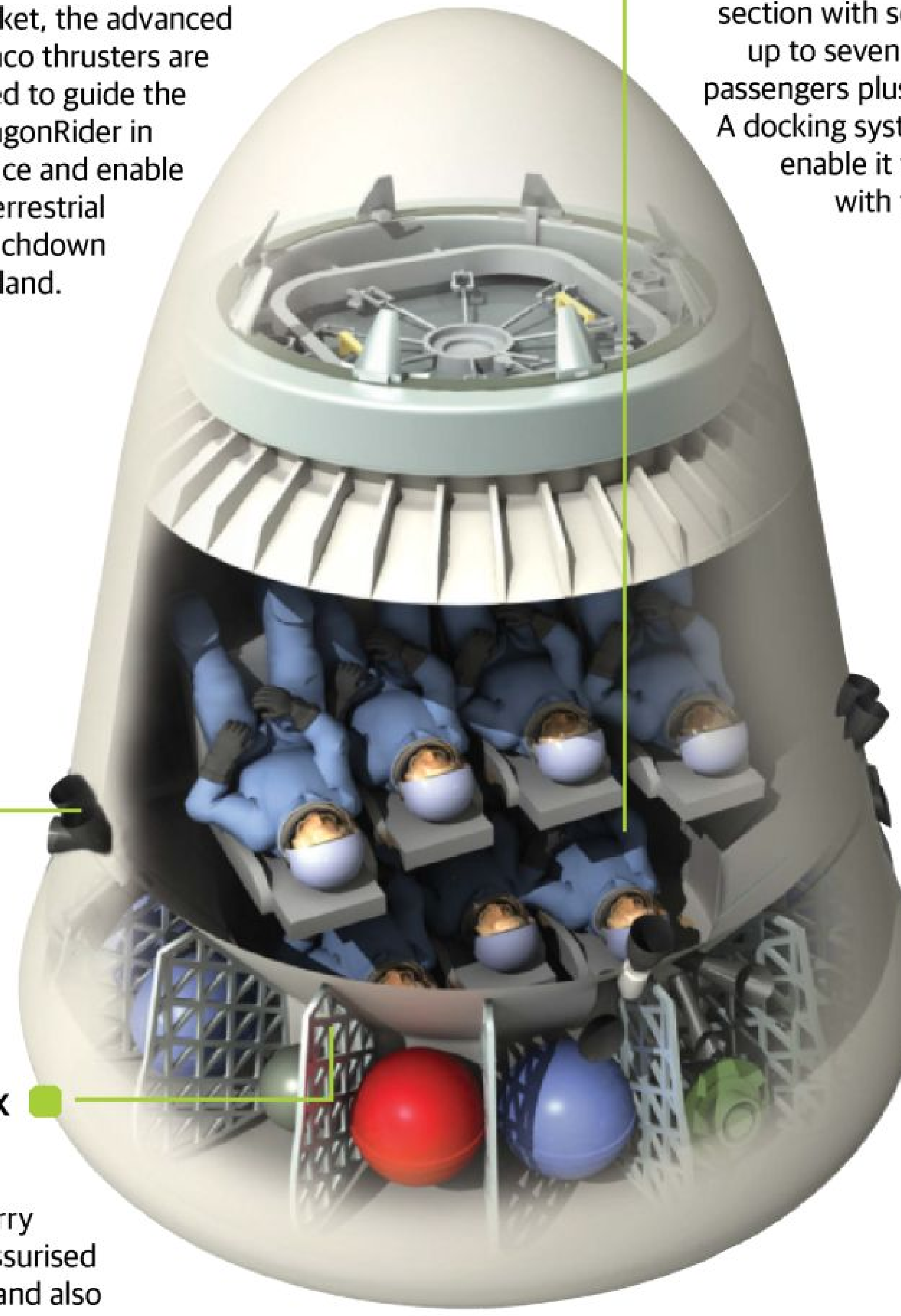
The DragonRider can take a crew of seven to the ISS

2. Fire-breathing vehicle

Name: DragonRider | **Launch date:** 2015 | **Mission:** Commercial crew transport

SpaceX, the private space transport company founded by Elon Musk, is in the process of creating the first commercial spacecraft to take a crew to the ISS. The plan is to put a manned Dragon spacecraft on its similarly proven Falcon 9 Heavy launcher. The two vehicles were developed with crew in mind, so it should only take a few modifications to the Dragon spacecraft to make it suitable for human spaceflight. This includes the most advanced launch escape system ever built, one that can use its SuperDraco thrusters to carry the spacecraft away from the Falcon 9 rocket in an emergency and land it safely in the ocean. Incredibly, SpaceX is developing a landing system that incorporates retro thrusters for a gentle touchdown on legs, as opposed to the parachute drop technique commonly used for current ISS expedition return journeys.

Like many of the commercial space ventures coming to the fore, SpaceX is a pioneer of more affordable solutions for delivering payloads into space, with the DragonRider spearheading the way into the new era of humankind's expansion into the Solar System.



Draco thrusters
Once it has reached its desired orbit and separated from the rocket, the advanced Draco thrusters are used to guide the DragonRider in space and enable a terrestrial touchdown on land.

Pressurised capsule
The DragonRider upgrade includes a pressurised section with seats for up to seven human passengers plus cargo. A docking system will enable it to dock with the ISS.

Trunk
The trunk can carry unpressurised cargo and also houses the DragonRider's solar arrays. The entire section is jettisoned before atmospheric re-entry.

SpaceX is pioneering affordable space flight for commercial companies

Red Rover will investigate caves on the Moon

3. Lunar spelunker

Name: Red Rover | **Launch date:** 2015 | **Mission type:** Lunar explorer

'Icebreaker' is the debut mission for Astrobotic, a competitor in the Google Lunar X Prize competition. It will launch via a Falcon 9 rocket, cruise to the Moon and land in a pit known as Lacus Mortis, 'the lake of death'. From here, the mission's Red Rover will explore its surroundings, including the entrance to a lunar cave network.

John Thornton

Astrobotic Technology Inc president

What was the inspiration for Red Rover/Icebreaker?

X Prize for Astrobotic was a catalyst. When X Prize was announced, it just made sense to launch the company and jump into the race. Our approach is to create a lunar delivery service capable of bringing payloads to the Moon at prices that the world has never seen. Right now, we're actively selling payloads aboard the mission, you can buy a pound of payload for $550,000 and it all scales. NASA did a study and figured out that it was costing them $10 million per pound to deliver the payload they need to the Moon.

Assuming all goes well, how long do you hope Red Rover will last?

Our intended landing site is called Lacus Mortis, it's a pit on the Moon otherwise known as a skylight. It's 100 kilometres (62 miles) across and 100 metres (330 feet) deep and when you get down to it, it's an entryway to a lunar cave network because there's lava tubes underneath the surface. We're designing this system to last a lunar night, the challenge there is that the temperatures get down to that of liquid nitrogen, -196 degrees Celsius (-321 degrees Fahrenheit), which is challenging for a lunar rover to survive. We're designing for that - we're not promising we can do that, but that is our intention.

What do you hope to achieve? What's the ideal outcome?

X Prize is just the base line. So our first mission will win the X Prize, collect a NASA contract called ILDD (Innovative Lunar Demonstration Data), which is a $9.5 million contract for data related to the Moon landing. It will also carry at least a dozen other payloads with us. So there will be objectives of those payloads that will become part of that mission as well.

What does the future hold for Red Rover and Astrobotic?

Astrobotic in the long term is about lunar payload delivery. That's our first goal in space. Then, from a big picture standpoint we're a space robotics company. We're going to make robotics in space for a long time to come and lunar delivery is our first go in the space industry.

4. Moon observatory

Name: Chang'e 3
Launch date: December 2013
Mission type: Lunar explorer

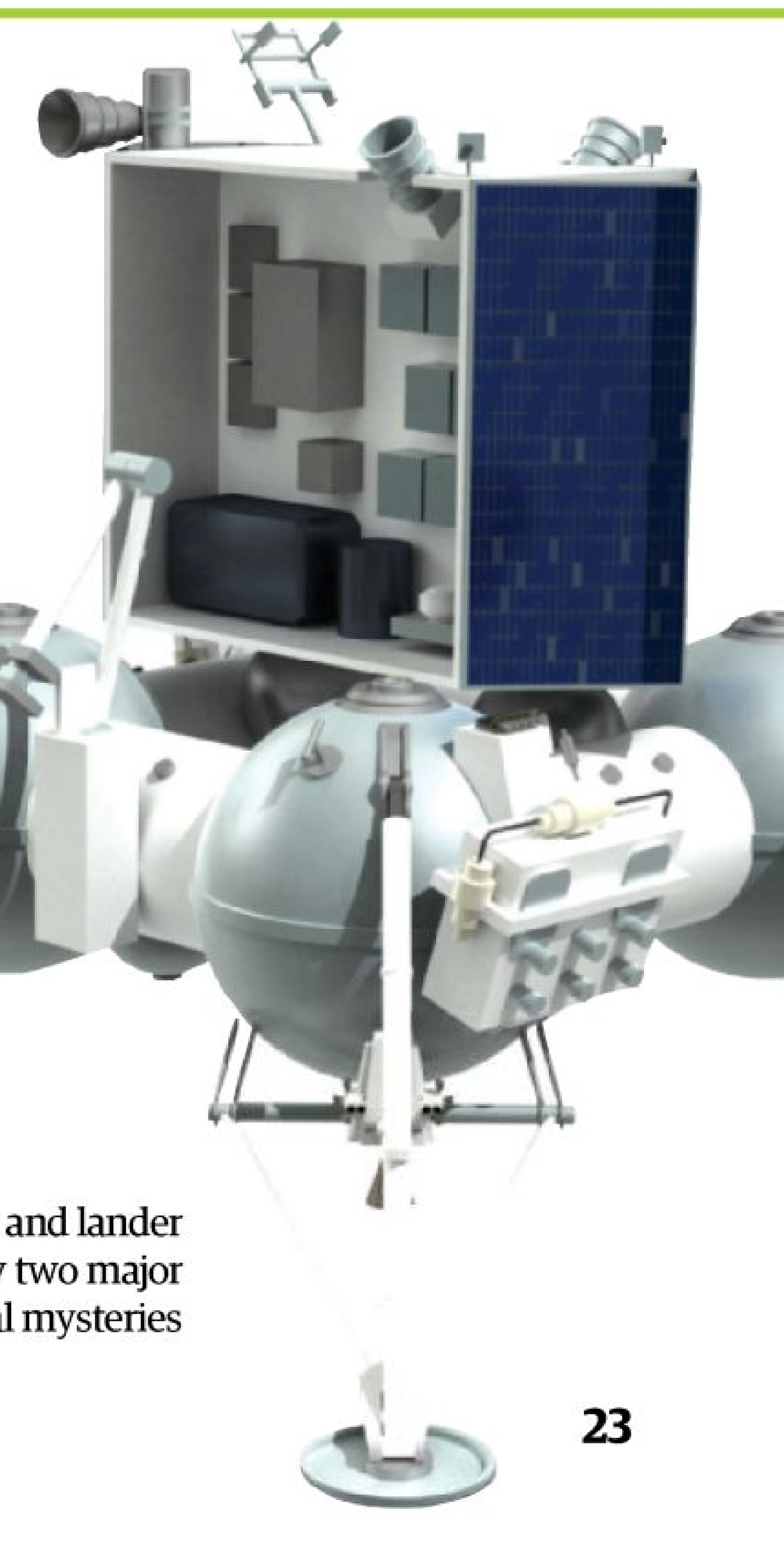
China's robotic explorer represents its first lunar rover mission. The vehicle will houses seven instruments, including an extreme ultraviolet camera that points towards Earth to investigate the effect of the Sun on Earth's ionosphere, plus a radar that will sees Moon's internal structure. It is be the world's first lunar-based astronomical observatory.

5. Cosmic ray detector

Name: Luna-Glob 1 | **Launch date:** 2015 | **Mission type:** Lunar surveyor

The Russian Federal Space Agency's next mission to the Moon is of the orbiter-surveyor variety, but to simply call it an orbiter-surveyor wouldn't do it justice. Luna-Glob 1 will be launched to the Moon some time in 2016 where the lander will use four surface penetrators salvaged from the cancelled Japanese mission Lunar-A. Weighing in at 45 kilograms (100 pounds) apiece, they will punch into the lunar surface where they will pick up Moon quakes generated deep in the lunar interior. This data, along with that of past seismic experiments such as those conducted by Apollo 11 and 12, will be used to help determine the origin of the Moon. Lunar-Glob 1's orbiter is scheduled for 2016 and using a payload of instruments, will embark on a study of high-energy cosmic rays. Between orbiter and lander, Lunar-Glob 1's objectives include the study of two of the most intriguing mysteries that have evaded scientific explanation for decades.

"They will punch into the lunar surface"



Orbiter and lander will study two major astronomical mysteries

Two brave volunteers will be the first humans to travel to Mars and back to Earth again

6. Mars and back

Name: Inspiration Mars | **Launch date:** 5 January 2018 | **Mission type:** Mars manned flyby

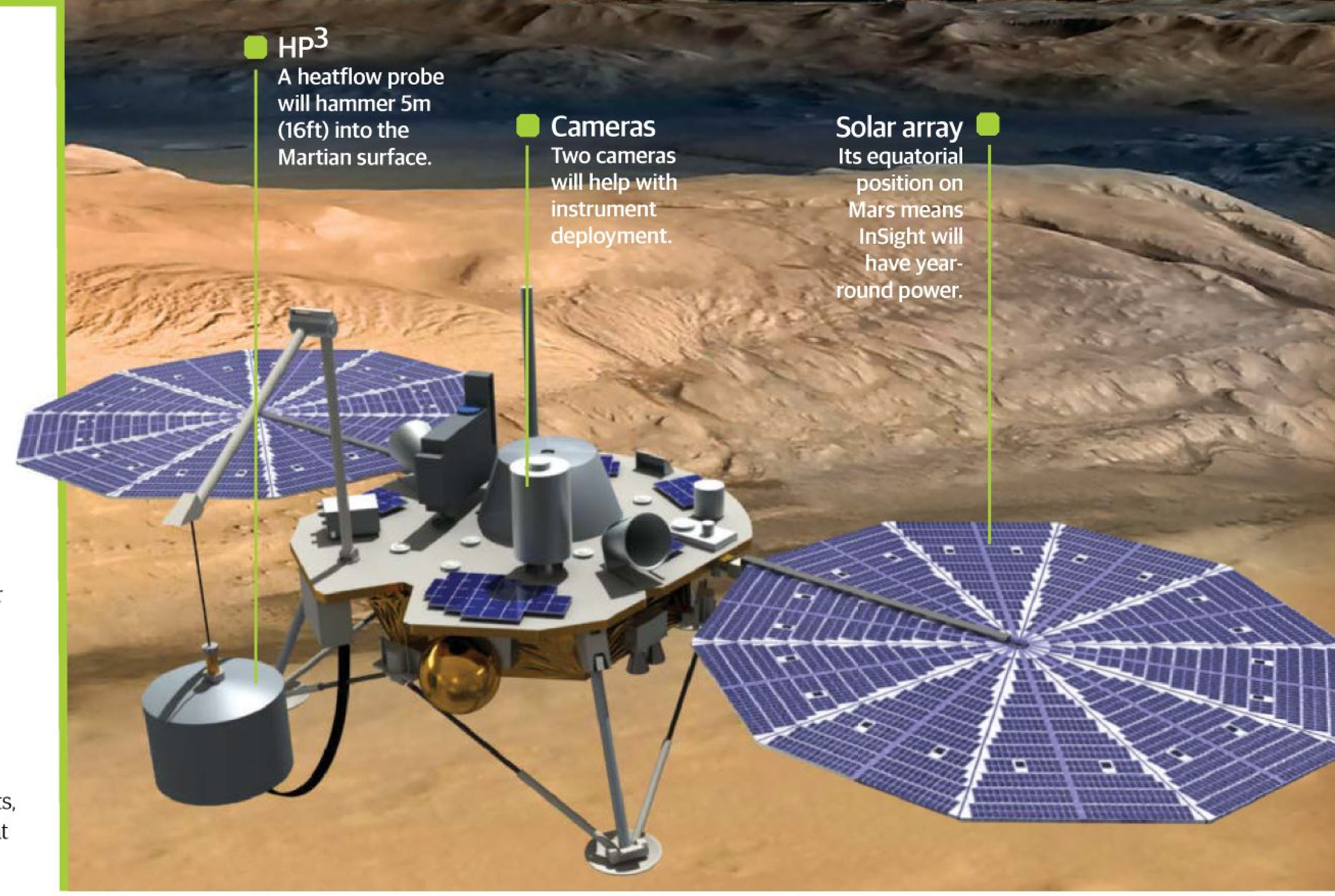
Founded by American engineer and former JPL scientist Dennis Tito, Inspiration Mars plans to put a US couple on a spacecraft to Mars and back again. Using established technology, it will look to take advantage of a fortuitous planetary alignment. In 2018 the planets will position themselves in such a way that a Mars flyby within 160 kilometres (100 miles) of the Martian surface and a return to Earth can be completed in just 501 days. Furthermore, the alignment will allow the spacecraft what's known as 'free return', where the gravity of the planets will bring the craft back to Earth at no extra fuel cost. The health implications of the mission to its two-man crew aren't insignificant: there's a marginal increase (no more than three per cent) in the chance of fatal cancer from cosmic radiation and the extended time spent in microgravity will take its toll. But in terms of setting a benchmark, even without setting foot on Mars, the success of this mission will undoubtedly prove as invaluable to science as the next generation of Americans it explicitly seeks to inspire.

> "There's an increase in the chance of fatal cancer"

7. Planet-cracker

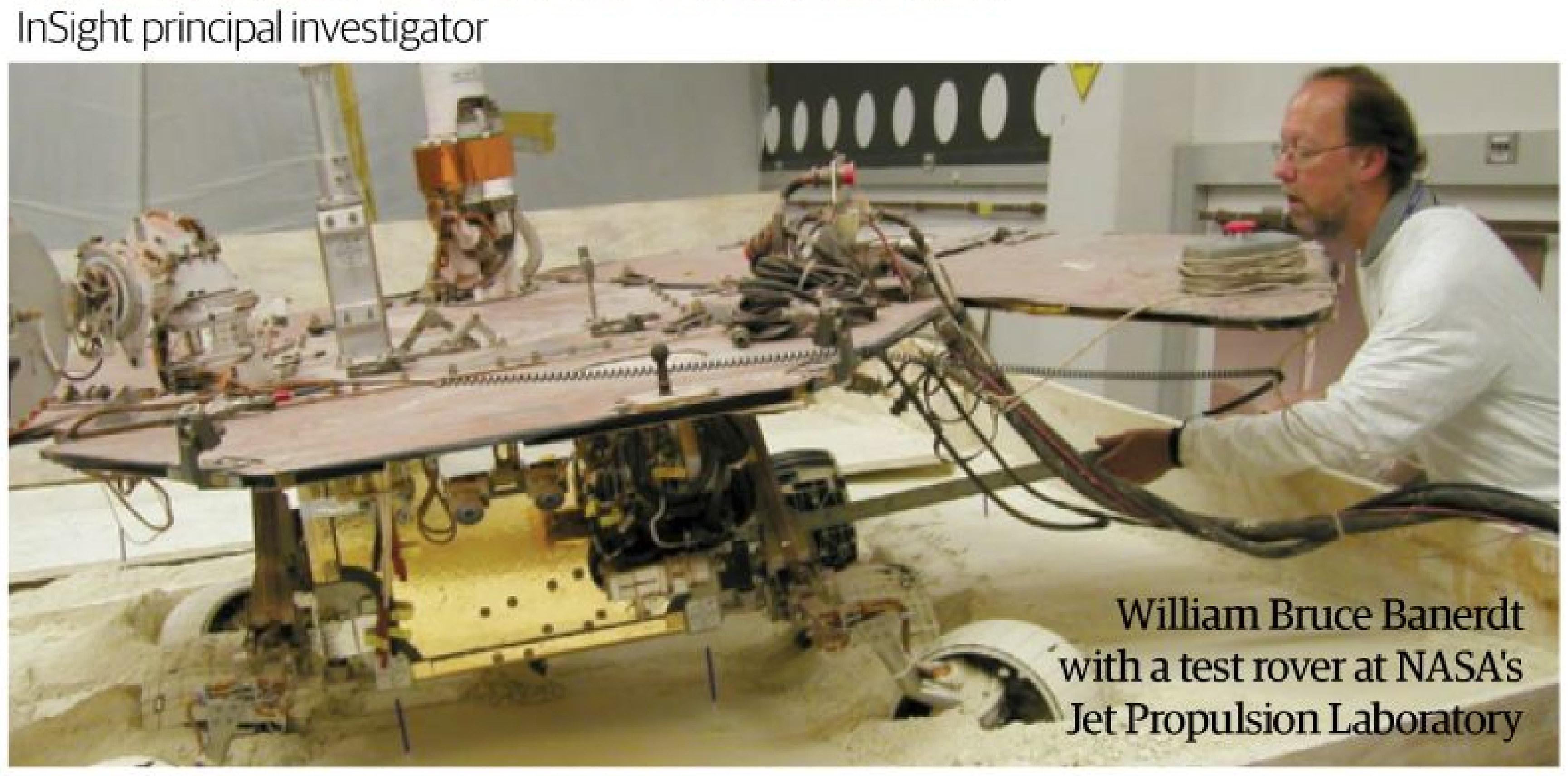
Name: InSight
Launch date: March 2016
Mission type: Mars Lander

InSight is a collaborative project between the US, German and French space agencies. The lander's primary mission will be to record data from the Martian interior, determining the thickness, composition and temperature of the various layers of the planet. This data will then be used to further our knowledge of how terrestrial planets - rocky worlds such as those found in the inner Solar System - form and evolve. Mars has been chosen for this study not just because of our experience landing on the surface but because, unlike the Earth, Venus and Mercury, it's big enough to have borne the processes that have shaped the terrestrial planets, yet small enough to have retained that signature from crust to core.



William Bruce Banerdt

InSight principal investigator

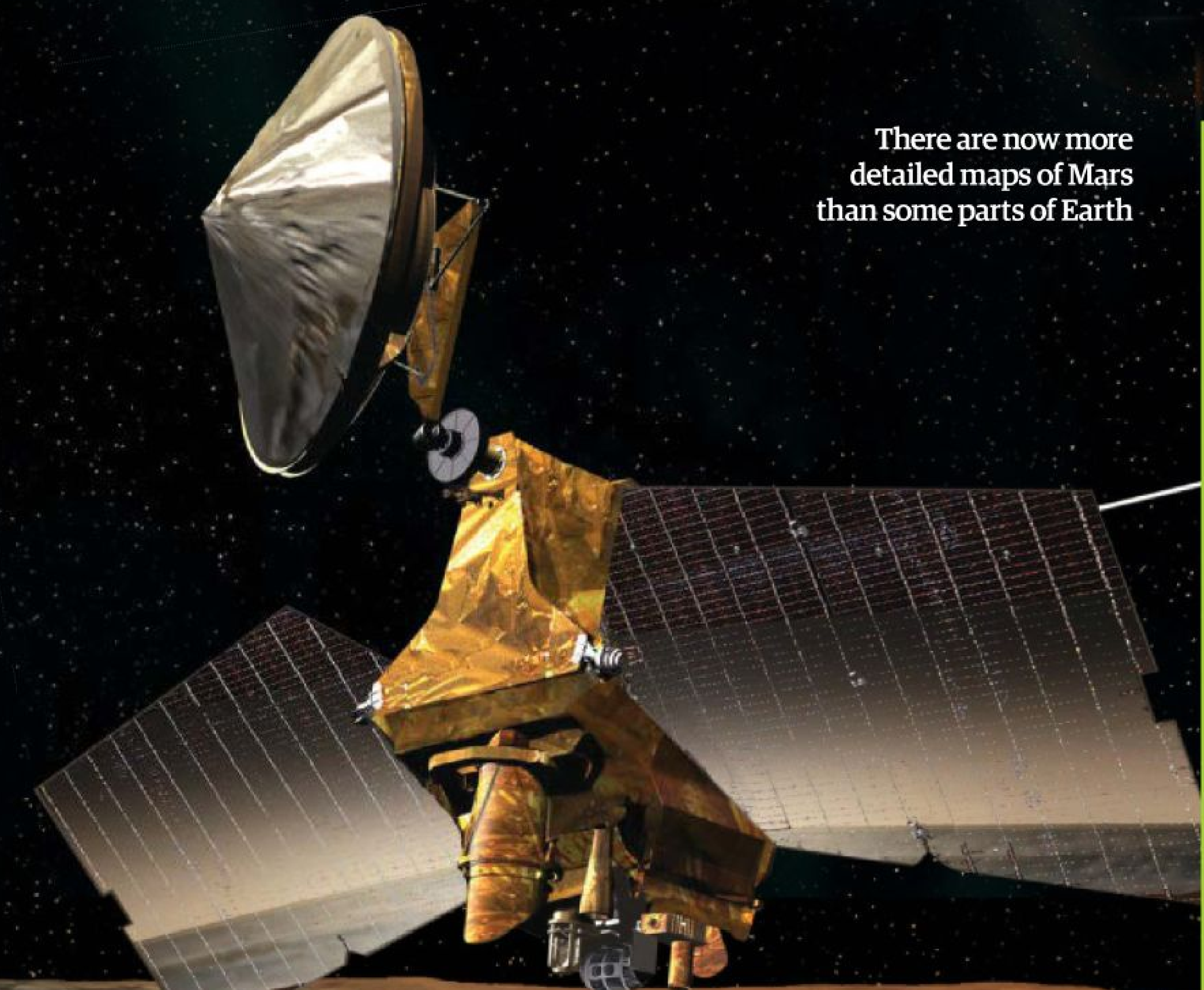


William Bruce Banerdt with a test rover at NASA's Jet Propulsion Laboratory

Can you explain why measuring the rate of meteorite impacts on Mars is so important?
We use the number of craters to estimate the age of the surface. To do that better, we need to know the rate at which they are formed.

What do you expect InSight to discover during its mission to Mars?
We hope to use the measurements that InSight will make about the structure and composition of the deep interior of Mars to help us understand how the rocky planets formed and evolved.

Could InSight perform its objectives on another planet?
Yes. Many of the same measurements could be made on either Venus or Mercury, although each of those planets have limitations. But our current knowledge is so sparse that such measurements on any of the rocky planets of our Solar System would be extremely valuable. The fact that we have so much other information about Mars from the many missions over the past 40 years will help us tremendously in the interpretation of our data.



There are now more detailed maps of Mars than some parts of Earth

8. Planetary cartographer

Name: Mars Reconnaissance Orbiter
Launch date: 12 August 2005
Mission type: Mars orbiter

The Mars Reconnaissance Orbiter was launched at a time when two rovers were exploring the Martian surface and three other orbiters were already circulating the Red Planet, including the Mars Global Surveyor, which had been in operation since 1996 and was on its third extended objective. It's had a lot to measure up to, but NASA's grand plans for the 2,180-kilogram (4,800-pound) spacecraft with its diverse payload of scientific instruments and cameras, have already been achieved in spectacular fashion. Designed to map the Martian surface, analyse its weather and search for liquid water, MRO has already trumped its predecessors by transmitting over 100 terabits of data back to Earth. That's more than every other interplanetary probe ever, combined. By November 2008, MRO had completed its detailed mapping of the Martian surface, providing extensive data on potential landing sites for future surface exploration missions that included the Gale Crater landing site for the Mars rover Curiosity. Now in its fifth year of extended missions since its primary was completed, MRO continues to look for liquid water as well as search for the remains of its two lost siblings: the Mars Polar Lander, which unexpectedly ceased communication shortly after its descent to the planet in 1999 (likely due to a high-velocity impact after an engine failure) and the ESA's Beagle 2, which fell off the radar after separating from the Mars Express Orbiter in 2003. It will also continue to be a communications and navigation medium for landers and rovers, for the remainder of its useful life.

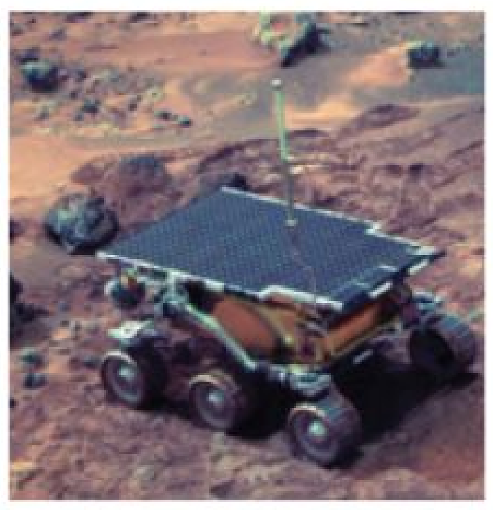
NASA's Mars missions have had a spectacular success rate in the last decade. Is InSight capable of going beyond the end of its primary mission like the Mars rovers?
We are designing the InSight mission to have high reliability in order to assure that it can meet its primary mission. If we do a good job and if Mars does not throw something unexpectedly difficult our way, we hope to be able to continue operating and making our scientific measurements beyond our one-Mars-year goal.

What would be the next step, once the InSight mission has come to an end?
For the geophysical questions that we have about how planets form and work, the next step would be to put multiple landers (say, three to six) on the surface at the same time. This would allow us to make much higher resolution measurements (using techniques developed for such science on Earth) and to begin to map out variations across the planet, to refine the average planetary values that InSight will return.

Mars explorer family

Launch date: 1997 onwards | Mission type: Mars rovers

Currently, NASA is enjoying a considerable hit rate with its Martian rovers. It's the only space agency to achieve any success moving across the planet, despite the early efforts of the USSR in the Seventies and the ESA's fated Beagle 2. Following Sojourner's short but sweet two-month life exploring the surface as the first successful Mars rover, its bigger brothers Spirit, Opportunity and Curiosity have increased both in size and ambition. The proposed Mars 2020 mission will build on both the established science and technologies of previous Mars rover missions.



Sojourner
Launch date: 4 July 1997
Status: Mission completed in 1997, final location unknown

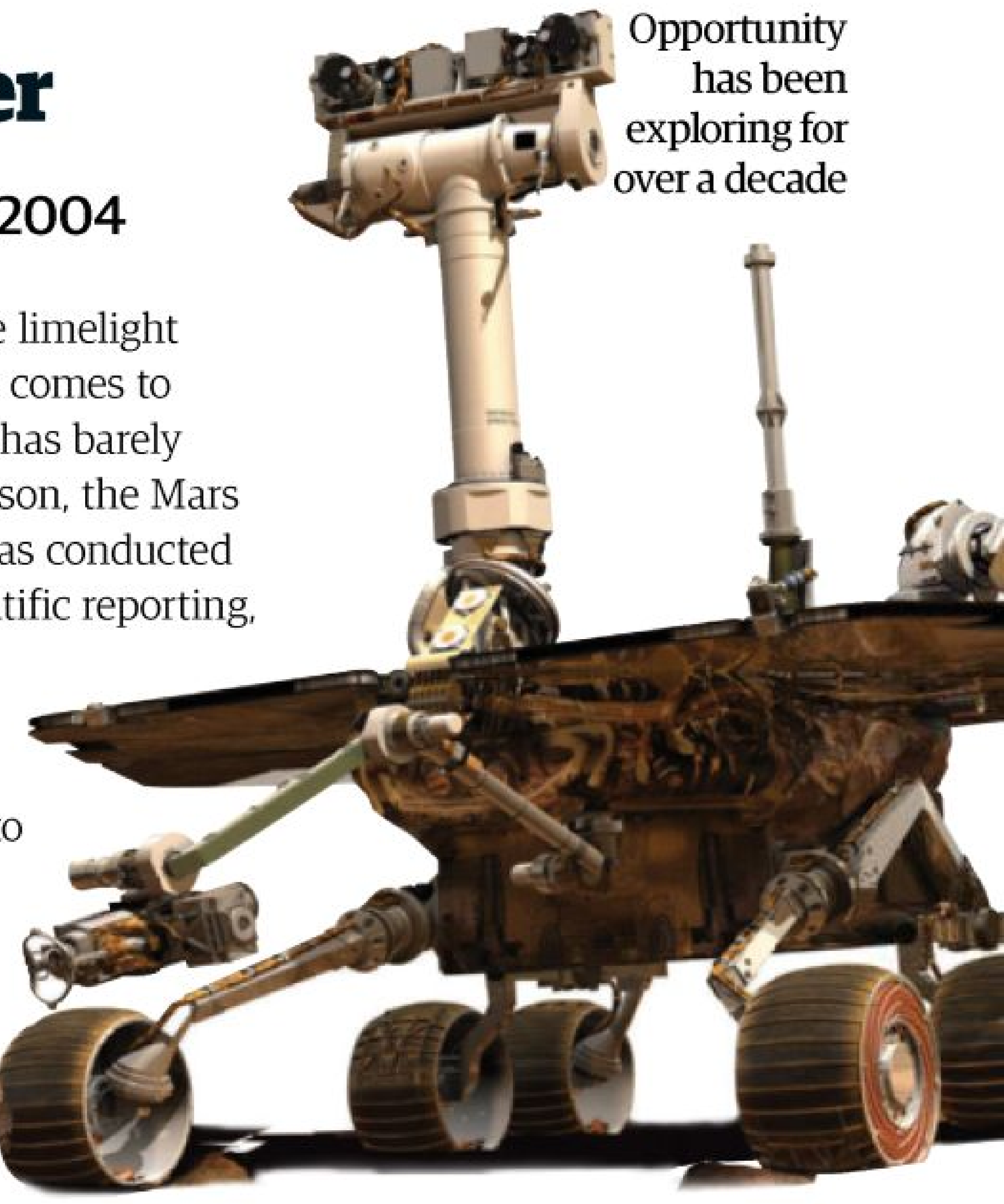
Spirit
Launch date: 4 January 2004
Status: Mission completed in 2011

Curiosity
Launch date: 6 August 2012
Status: Active

9. Overachiever

Name: Opportunity
Launch date: 25 January 2004
Status: Active

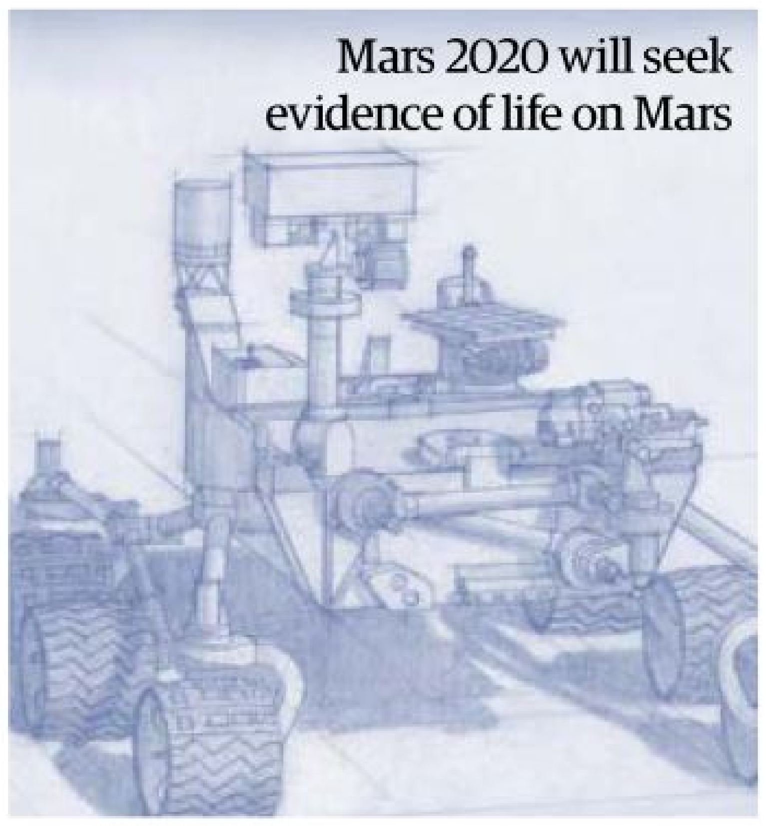
Curiosity might have grabbed the limelight from its older sibling, but when it comes to being an achiever, the youngster has barely begun to prove itself. By comparison, the Mars Exploration Rover Opportunity has conducted a decade of exploration and scientific reporting, nearly 40 times the life span it was designed for, surviving environmental and mechanical adversities that have threatened to kill the mission and contributing substantially to the investigation of water on Mars as well as its atmosphere and weather. It continues to gather data and explore to the present day.



Opportunity has been exploring for over a decade

10. Future rover

Name: Mars 2020 | Launch date: 2020 | Status: Mission proposal



Mars 2020 will seek evidence of life on Mars

While the next proposed Martian rover isn't any particular leap in technology over MSL's Curiosity (it will use much of the same design as the current Mars rover), the opportunities that Mars 2020 affords are nothing to be sniffed at. One of the rover's objectives will be to collect specimens from the surface to be collected by a near-future sample-return mission and, ultimately, demonstrate the viability of technologies in preparation of a manned mission to Mars.

11. Prospector

Name: OSIRIS-REx | **Launch date:** Late 2016 | **Mission type:** Asteroid sample return

The Origins Spectral Interpretation Resource Identification Security Regolith Explorer (OSIRIS-REx) mission is probably one of the most exciting missions set to launch in the next few years. NASA intends to send the 1,529-kilogram (3,370-pound) spacecraft on a three-year journey to an asteroid around 575 metres (1,900 feet) in diameter known as 101955 Bennu, which follows a very similar orbital path to the Earth. Once it reaches 101955 Bennu, OSIRIS-REx will land on the asteroid and then spend 505 days making various readings and measurements, before taking a sample of the asteroid and returning to Earth in 2023. As a rare, large carbonaceous asteroid, it is hoped that the 101955 Bennu sample will provide many clues as to the formation of the Solar System and, perhaps, life on Earth.

Simply proving OSIRIS-REx can return a sample will be success enough

"If we find a monolith, we'll definitely be going back"

Ed Beshore, OSIRIS-REx project

Ed Beshore

Deputy principle investigator, OSIRIS-REx project

Why asteroid sampling?
Despite the fact that we know a lot about the Solar System, we really don't know where the water came from. Was it already bound up in the rock that formed the Earth, or was it delivered to the Earth by comets or other bodies that might have picked it up at the edge of the Solar System? So what we're looking for is that place where we can go to study this.

What do you expect to find in it?
We're interested to know how water is bound up in the asteroids, about the sources of organics, we do often find the base constituents of DNA in asteroids and in addition we're looking at space weathering.

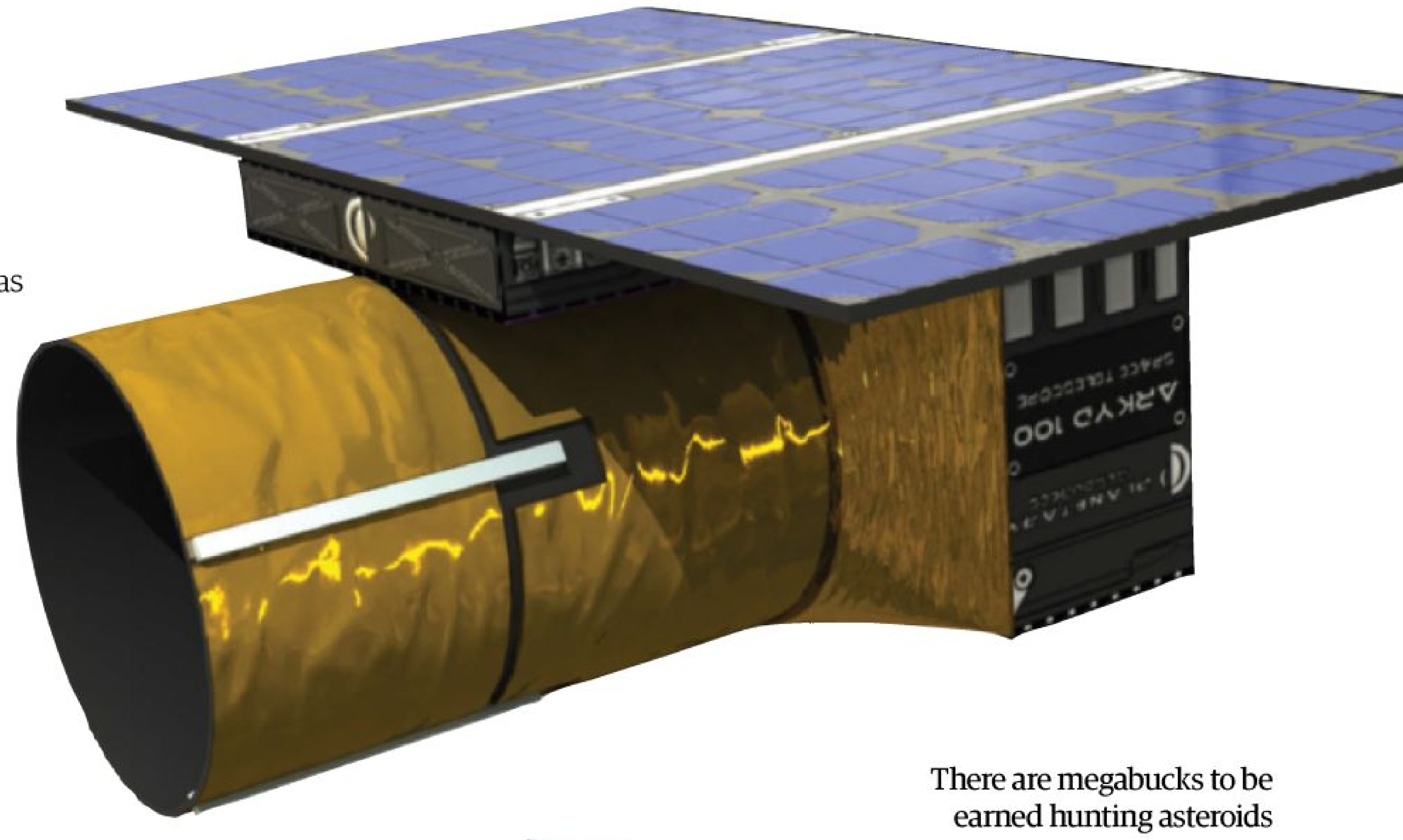
You're mapping Bennu too – is it possible you'll return there?
Certainly if we determine that it's an existential threat to the Earth, I daresay we would. For scientific grounds? If we find a monolith we'll be going back [laughs] but otherwise we'll probably want to go off to other asteroids to see what's different.

What's the ideal outcome when you get the sample back?
I think that getting the sample back is actually the ideal outcome. It's basically our criteria for success: it's the return of a sample of at least 60g (2oz). About 45g (1.6oz) or so we can archive and not have to touch. We can get everything we need that's laid down in our mission objectives from just 15g (0.5oz) of material. It so happens that in our testing done in microgravity flights, we've actually picked up something closer to 2kg (4.4lb). So we know we have the capability to pick up a considerable sample, a larger sample than what we brought back from the Moon. If we bring back a sample like that, it really doesn't matter what we find out, the fact that we are able to do that and to analyse these samples, will really be the mission success. We'll demonstrate something really important in doing that.

12. Asteroid hunter

Name: Arkyd-3 | **Launch date:** 2014 | **Mission type:** Satellite

Planetary Resources, the asteroid mining company, begins its first foray into space next year. The Arkyd-3 'CubeSats' are a stepping-stone technology, a series of tiny satellites just 30 centimetres (12 inches) long that will test the hardware preceding a mission to send Arkyd-100s to scout for prospective asteroids. Despite the diminutive size and experimental status of its technology, the Arykd-3 mission is the first step towards a none-too-distant future that has previously been the subject of pure science fiction until now. From here, Planetary Resources will move towards mining water, minerals and precious metals from near-Earth asteroids: from spotting resource-rich asteroids, to tracking them, to exploring and recovering material to transport back to Earth.



There are megabucks to be earned hunting asteroids

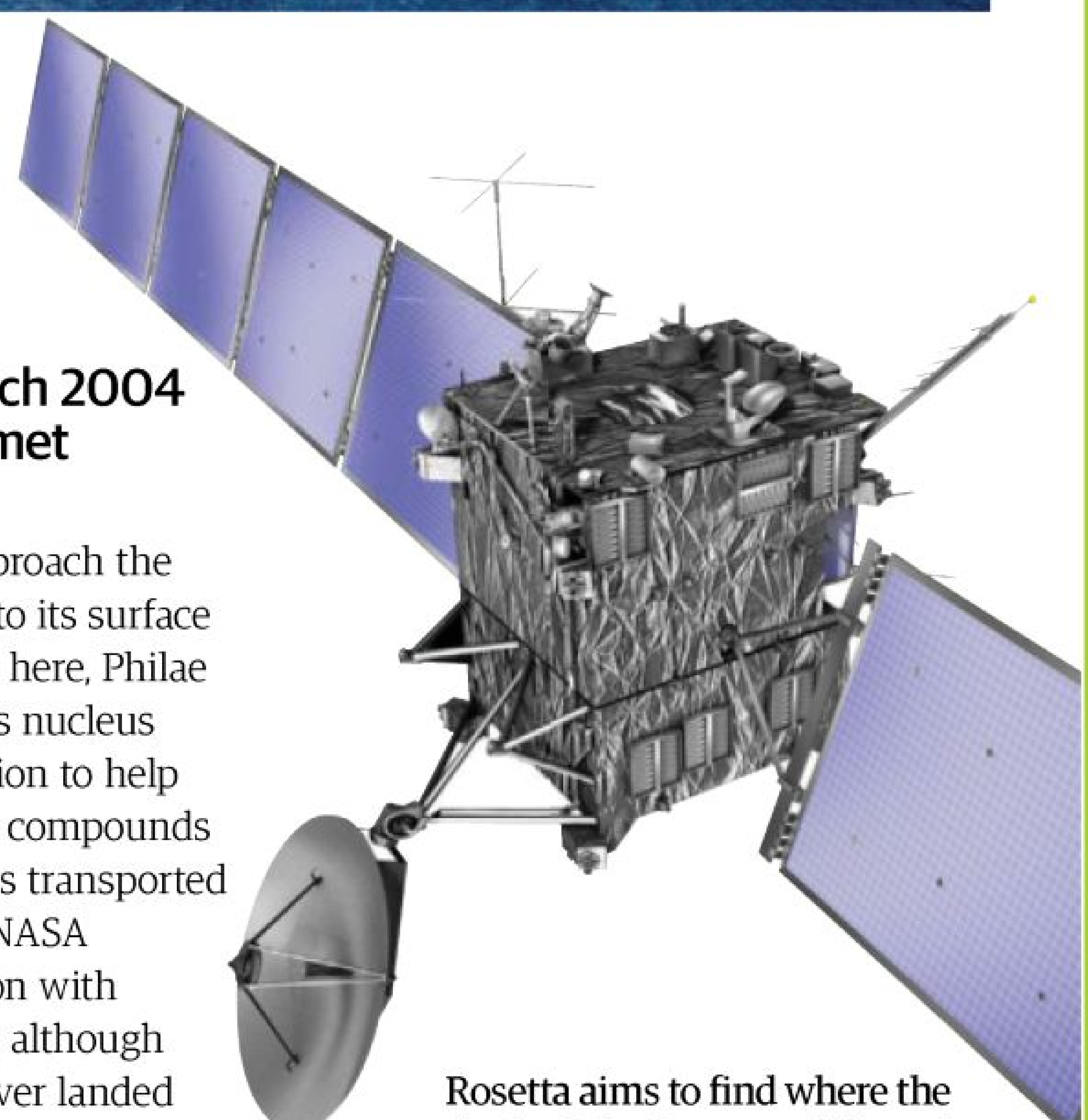
"The first step towards a science-fiction future"

The Rosetta mission team at the European Space Agency

13. Comet chaser

Name: Rosetta
Launch date: March 2004
Mission type: Comet orbiter/lander

If it meets its main objectives in 2014, the European Space Agency's Rosetta mission will be one of the few spacecraft to successfully orbit and land on a comet. Travelling out of the asteroid belt to a distance of around Jupiter's orbit, Rosetta will rendezvous with its target, comet 67P/Churyumov-Gerasimenko, where it will begin its approach. By mid-2014 it will be orbiting the comet and mapping its surface before releasing a lander called Philae. This lander will approach the comet, firing a harpoon into its surface in order to anchor it. From here, Philae will investigate the comet's nucleus and its chemical composition to help us understand the organic compounds of comets and how water is transported around the Solar System. NASA conducted a similar mission with comet 9P/Tempel in 2005, although the Deep Impact probe never landed on its target comet.

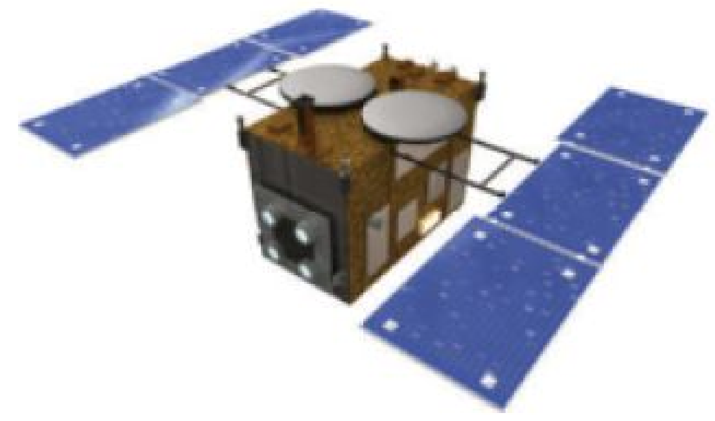


Rosetta aims to find where the water in the Solar System originated

14. Earth defender

Name: Don Quijote
Launch date: 2015
Mission type: Asteroid orbiter, impactor and lander

This three-part ESA mission is a test to see whether an asteroid can be deflected from a collision course with Earth. Don Quijote will study the asteroid while an impactor smashes into the surface, before a lander is released on to the surface for closer scrutiny.



15. Rock hound

Name: Hayabusa 2
Launch date: 2014
Mission type: Asteroid survey

JAXA, the Japanese space agency, is sending Hayabusa 2 to an asteroid to learn more about the early Solar System and the origins of life on Earth. Once at Apollo asteroid (162173) 1999 JU3, the spacecraft will hit it with a 2kg (4.4lb) impactor, examine the crater and take a sample.

Dawn has already observed Vesta

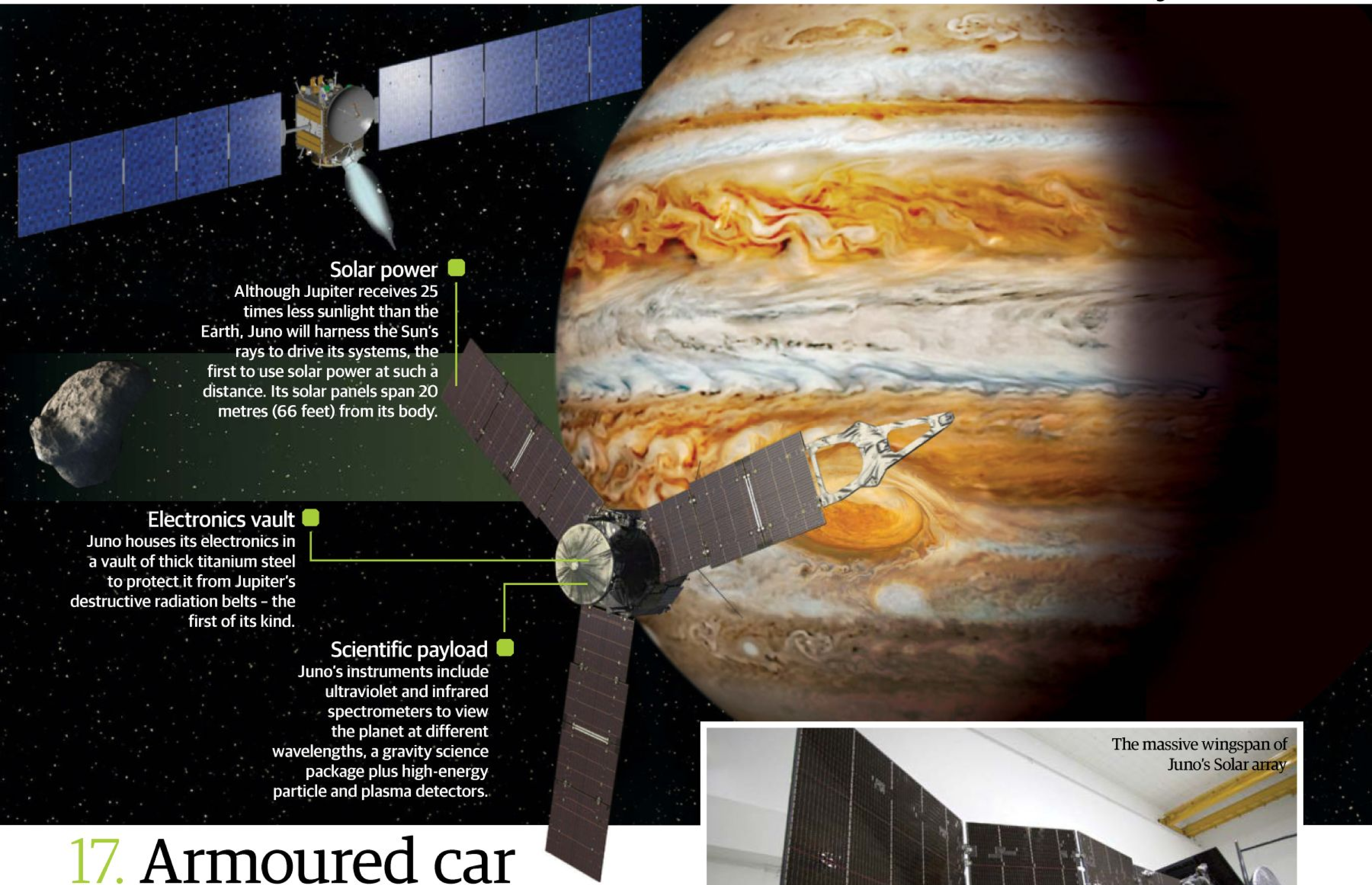
16. Giant slayer

Name: Dawn
Launch date: 27 September 2007
Mission type: Asteroid orbiter

The Dawn spacecraft has the distinction of visiting two of the most massive asteroids in the main asteroid belt of the Solar System, the 525-kilometre (326-mile) diameter Vesta and the only dwarf planet in the inner Solar System, Ceres. Like several other asteroid-investigating spacecraft, Dawn is tasked with providing data that will help scientists to determine the role of water in the Solar System and how it has affected the evolution of the planets.

Dawn has already entered orbit around Vesta and made its observations, which included the discovery of a metallic core approximately 220 kilometres (137 miles) in diameter. Having broken from Vesta's orbit, Dawn is scheduled to reach dwarf planet Ceres in early 2015, where it will enter an incrementally lower orbit, settling at an incredibly low altitude of 700 kilometres (434 miles). Visiting a third asteroid belt target might also be possible.

"Dawn will help scientists determine the role of water in the Solar System"

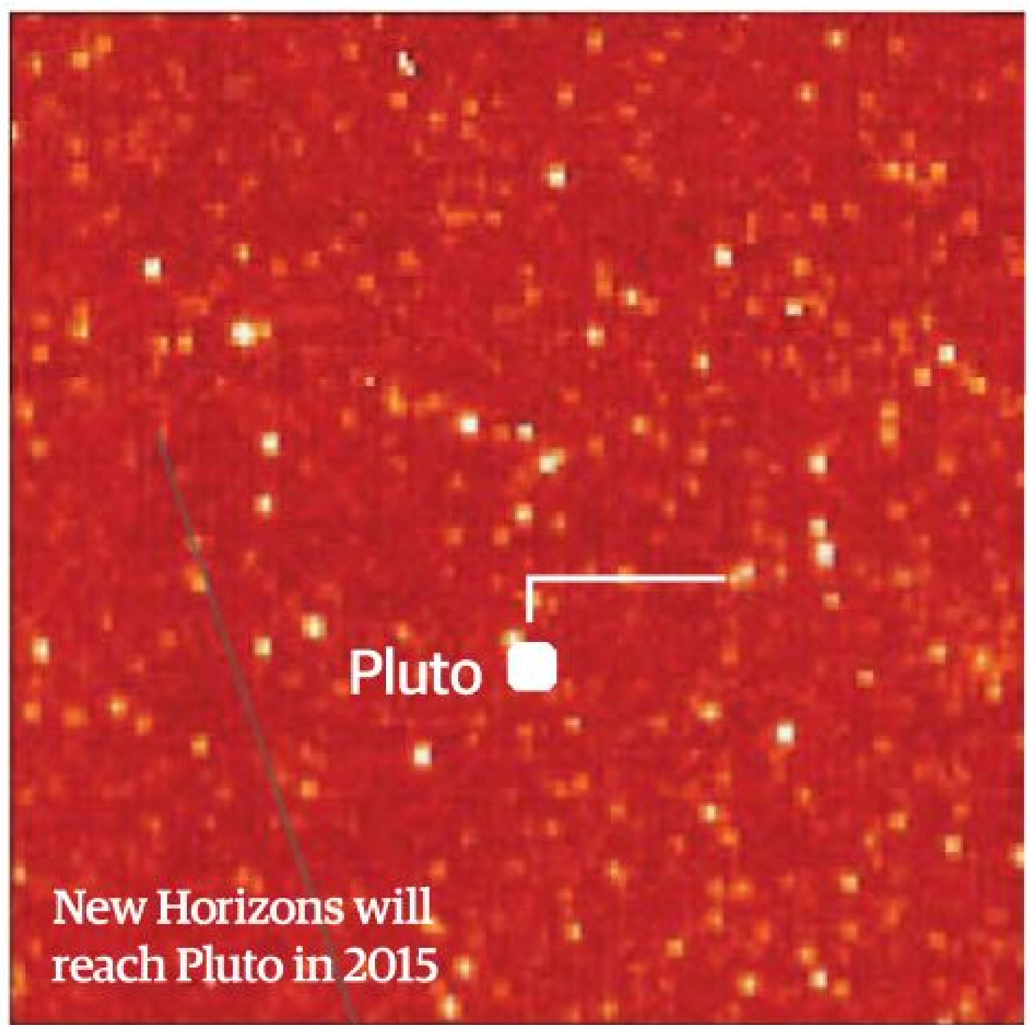


The massive wingspan of Juno's Solar array

17. Armoured car

Name: Juno | **Launch date:** 5 August 2011 | **Mission type:** Jupiter orbiter

Due to arrive at Jupiter in 2016, Juno's main objectives will be to analyse the gas giant from its core outwards, from estimating its core mass and the composition of its various layers to mapping its magnetic field. Using this information we should get a much better idea of how Jupiter formed, from its youth as an early Solar System subnebula to its status as the biggest planet orbiting the Sun. Jupiter's treacherous radiation belt means Juno has an unusually elongated orbit that will allow it to slip past the worst of it, while its electronics will be shielded by a radiation vault with titanium walls.



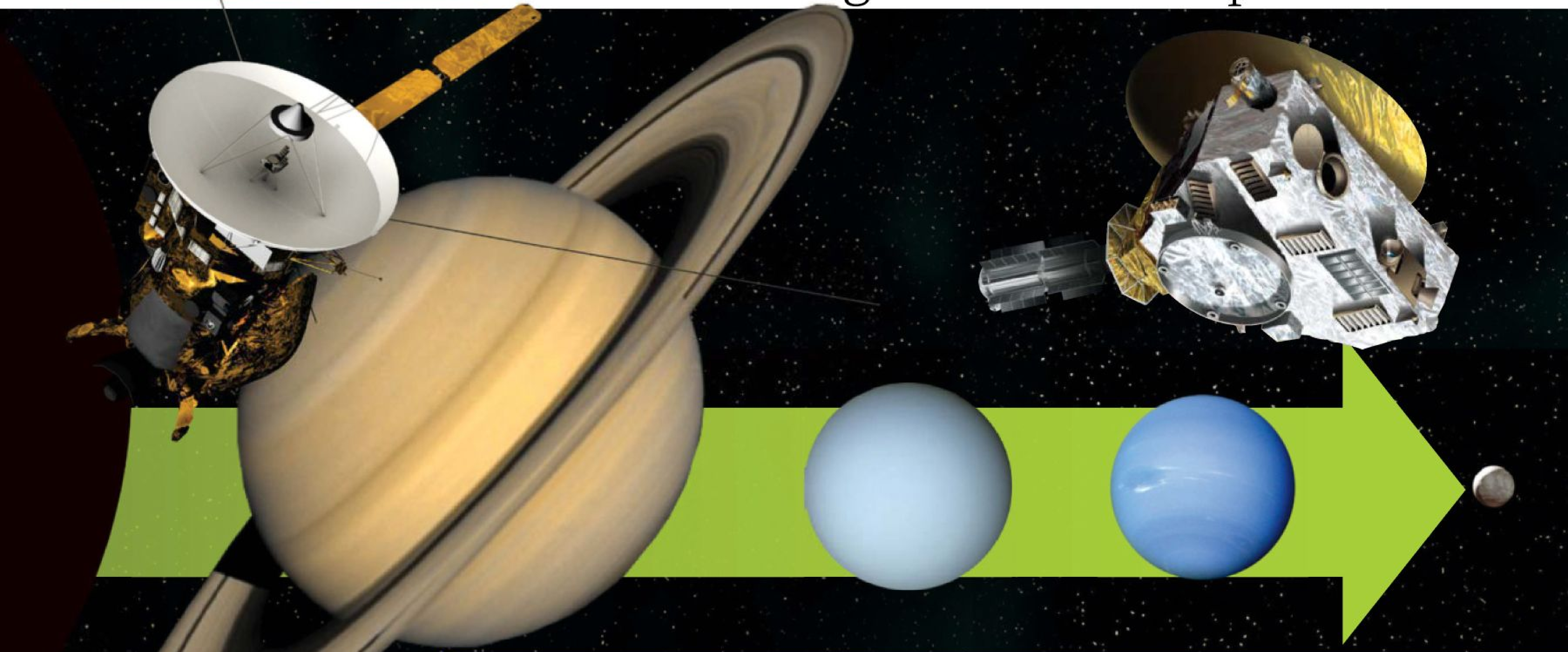
New Horizons will reach Pluto in 2015

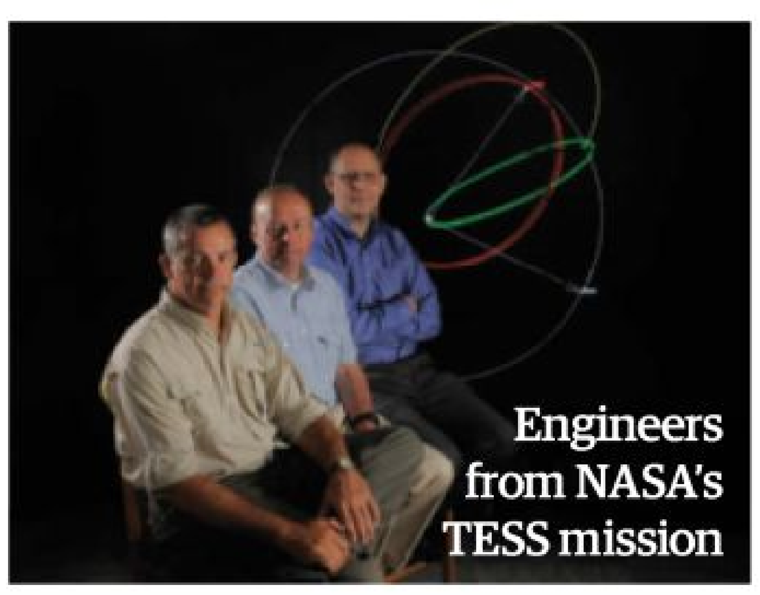
18. Frontier explorer

Name: New Horizons | **Launch date:** 19 January 2006 | **Mission type:** Pluto flyby

In just under two years, one of the most ambitious missions ever launched from Earth will reach its first target. The New Horizons spacecraft will arrive at Pluto in July 2015, by then having already taken images of the dwarf planet that exceed the best resolution snaps taken by the most powerful telescopes ever made. Detailed maps will be made of its daytime surface as well as observations of Pluto's composition, before New Horizons trains its sights on the moon Charon. Once it has conducted its flyby of Pluto and its moons, the spacecraft will move further into the Kuiper belt to target other objects before following a similar path as the Voyager probes, out into the heliosphere and the extreme reaches of the Solar System. New Horizons also holds the world record for the greatest launch speed of any man-made object, travelling at a relative velocity (to Earth) of approximately 58,000 kilometres per hour (36,000 miles per hour).

"It also holds the record for greatest launch speed"




Engineers from NASA's TESS mission

19. Planet hunter

Name: TESS
Launch date: 2017
Mission type: Space telescope

The Transiting Exoplanet Survey Satellite is an observatory that specialises in seeking out exoplanets using the transit method. By watching a parent star and any dimming in its brightness that occurs if an orbiting planet travels in front of it, the size of the planet can usually be determined. It will remain in an elliptical Earth orbit for two years, laying the groundwork for future exoplanet hunters like the James Webb Space Telescope.

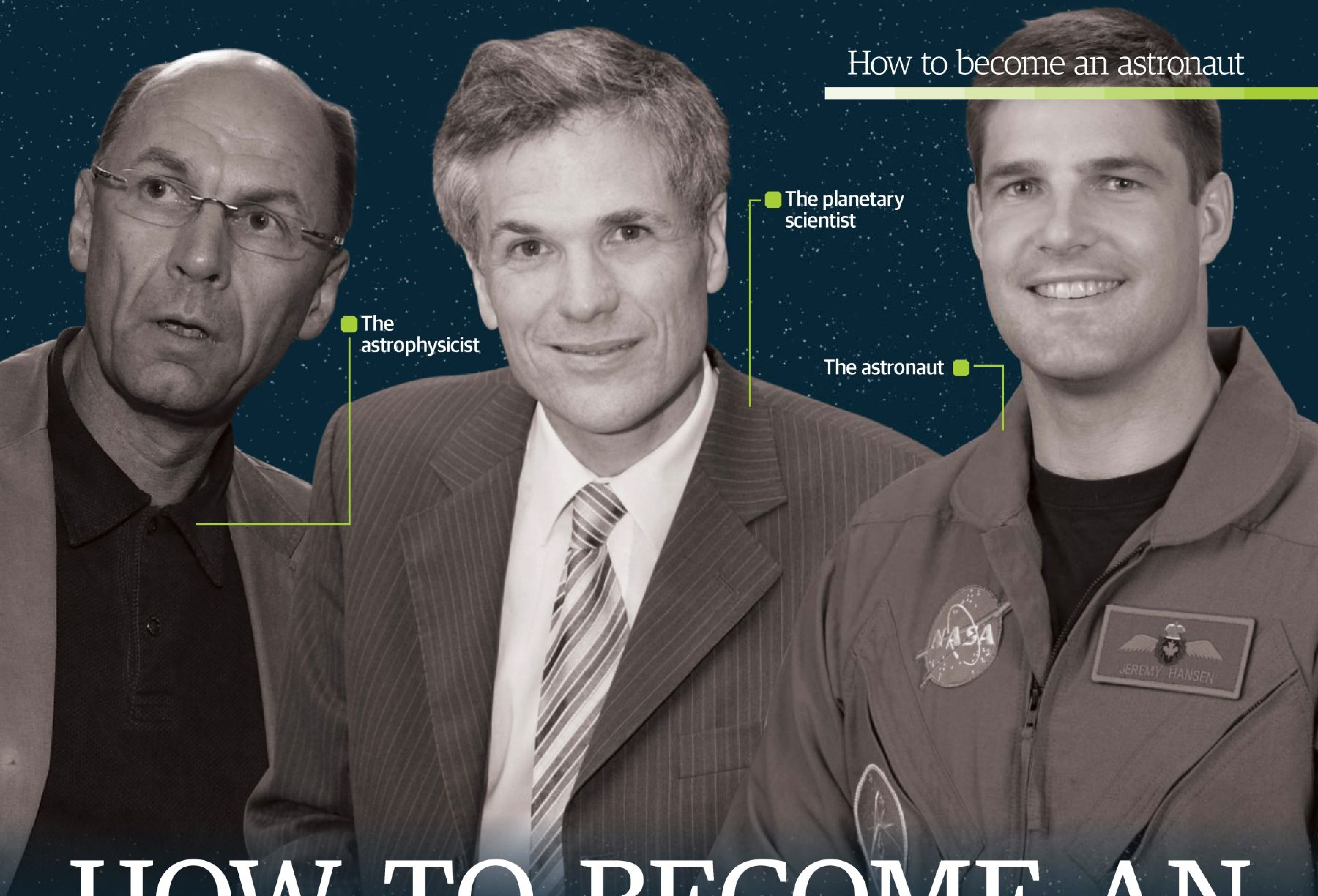
20. Ringed-planet observer

Name: Cassini-Huygens | **Launch date:** 15 October 1997 | **Mission type:** Saturn orbiter/lander


Saturn's invisible rings, one of Cassini's many discoveries

Cassini-Huygens has been one of the most prolific and successful space missions of its kind since its launch 16 years ago. Its main objectives included a detailed study of Saturn's rings, its atmosphere and its moons (discovering three new satellites in the process), plus a test of Einstein's general relativity theory. These objectives were completed by 2008, after which Cassini was in place to observe Saturn's Great White Spot storm rage across its northern hemisphere. It also captured a 'new' Pale Blue Dot photo of Earth from over 1.4 billion kilometres (900 million miles) away. ESA's Huygens probe was also dropped off by Cassini on to the moon Titan. Although Huygens only transmitted data for 90 minutes, it's the most distant lander ever sent.


The rocket engineer
The mission controller



HOW TO BECOME AN ASTRONAUT ...plus other cool space jobs

Is becoming an astronaut your dream? Want to spend your days exploring the stars? Find out how your career in the space industry could lift off

So much has happened since Neil Armstrong set foot on the Moon in 1969. Today, we have the International Space Station, plans to send manned missions to Mars, telescopes that can see beyond our Solar System and agencies across the world aiming to put men and women into space. If you would love to explore space as a career, you couldn't have picked a better time, especially given the number of private space tourism companies looking to send members of the public high above the Earth's surface.

A word of warning: it's not going to be an easy ride and you'll be entering a competitive arena of the best and brightest. If there were ever a stark example of why it pays to absorb as much as possible at school, the space industry is it. Unless you have a solid background in science and maths, showing great aptitude for both, many doors will be closed. It may sound negative, but it's very much the harsh truth.

If you make the grade though, the universe is your oyster. Space is one of the most exciting industry areas in the Solar System, with new advances and fresh breakthroughs taking place regularly. Whether you become an astronaut and find yourself on a rocket hurtling to a far-flung planet or love to bury your head in research and test cutting-edge theories, the possibilities are wide open. Who knows – you may even be the one who finally discovers life on another planet.

Over the next few pages we're going to take a look at the various cool jobs you can get stuck into. We speak to the people who are already involved and achieving great things, as well as those who are on the cusp of greatness and have already enjoyed long careers. We also look at some jobs that you may never have considered, all vital to further human knowledge of the universe. Good luck.

The astronaut

Take the next giant leap for mankind

BIO

Jeremy R. Hansen
Canadian Space Agency
Astronauts are trained to go into space either as a commander, pilot or crew member of a spacecraft. Having been selected in May 2009 as one of 14 members of the 20th NASA astronaut class, Major Hansen is one of two active Canadian astronauts. He trains in spacewalks and robotics, takes part in geological expeditions and he has even established a new training program to simulate a week on board the ISS.

Astronauts have a clear aim: to shoot into the darkness of space and explore to further human knowledge of the universe. Of all of the jobs in the space industry, this is potentially the most exciting and certainly the most-recognisable role.

It's not an easy job to get and there are certain barriers in your way before you can even start. Although jobs are increasingly available via private companies, opportunities tend to be restricted given that agencies recruit from their own citizenship. To be a NASA astronaut, you need to be an American citizen, ESA looks for Europeans and the Russian Space Agency wants Russians (Russian astronauts are called cosmonauts). What's more, each one is after a high standard of candidate.

The cost of training an astronaut is huge, so the agencies need to find the very best people from the outset. This is not a role you can learn at university and it will take years of preparation before a successful candidate jets off into space. Even then, flight opportunities are limited.

For those who are successful, a career as an astronaut is hugely rewarding. There are two types to choose from - pilots and mission specialists - but both suit people who want to learn and can do so quickly. Pilots will fly the shuttle and dock it with the ISS, or another satellite that needs servicing or retrieving. These pilots tend to be picked from the armed forces.

Getting accustomed to near zero-gravity is essential

Mission astronauts accompany the pilots and work on various research tasks, as well as repairing and maintaining equipment. The role evolves and needs fresh knowledge and understanding as the years go by. The job also needs operational skills, since Astronauts are often put in positions where things aren't going their way, making life uncomfortable, intimidating and scary. The key is how people react to the situation they're in - space agencies want people who can separate emotion from the situation and think critically, looking for solutions.

This means the training is varied and the job is demanding, fun and challenging. You'll find yourself in extreme situations on Earth and in space. You could be flown as part of a team to the Arctic on an aeroplane and left for days at a time to explore and survive, or you could be stationed on the International Space Station where you'll experience weightlessness in cramped conditions. It's all part and parcel of this amazing job.

In space it's hard to think about a typical day, since an astronaut will see 15 dawns every 24 hours. As well as trying to get into a new sleeping rhythm, astronauts need to work. On the ISS this may involve supervising experiments or maintaining station equipment. Work on the ISS is supported by astronauts on the ground, looking at how life in microgravity affects the human body, studying bone-loss or the effects of radiation levels. Spacewalks and robotics figure highly and it all helps to develop systems and processes that will one day see humans set foot on Mars. Astronauts training today may well get that opportunity within the lifespan of their career and there's no greater motivation than that.

"Astronauts are often put in positions where things aren't going their way"

CV

Education
You'll need a bachelor's degree in Engineering, Biology, Physics, Maths as well as an advanced degree (Master's level or above).

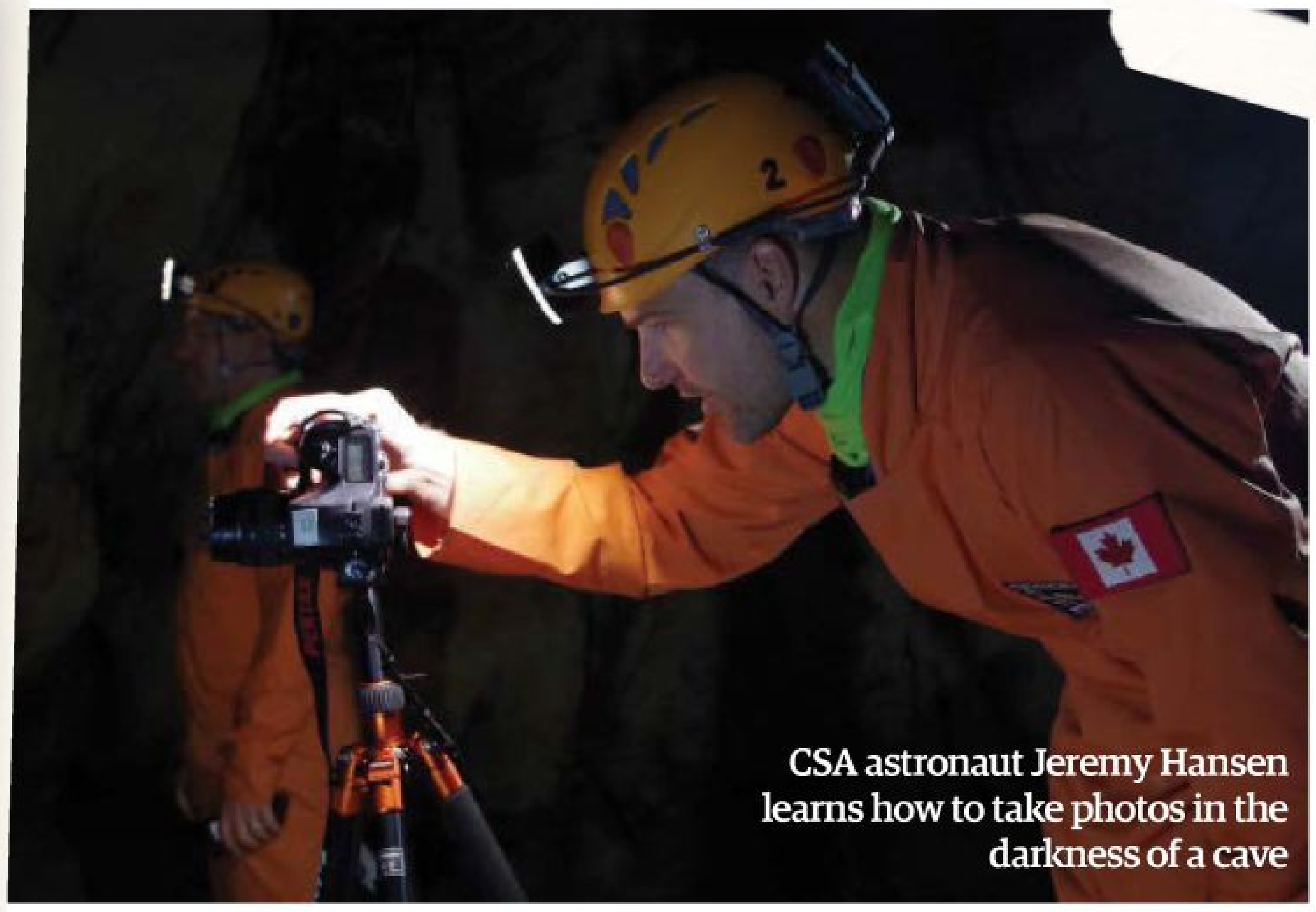
Wings
More than 1,000 hours pilot-in-command time in a jet aircraft, if you wish to be a pilot.

Physical fitness
NASA and other agencies will measure your vision, blood pressure, height and more.

Willingness to learn
Major Hansen believes this is the most vital asset of all.


Inspiring the next generation is also an important part of an astronaut's role


Jeremy Hansen's first EVA run in NASA's Neutral Buoyancy Laboratory


CSA astronaut Jeremy Hansen learns how to take photos in the darkness of a cave

Insider knowledge

What is it like being an astronaut?
Jeremy Hansen: I am trained to go into space by NASA at the Johnson Space Centre in Houston, Texas, but I'm hired for Canada. Currently we're not flying a lot of people into space but, in say five years from now, I think we're going to see some rapid changes developing, particularly with commercial companies getting involved, changing the map of how many people are flying in space and the types of things we're doing with respect to space exploration.

How did you become an astronaut?
JH: I have a specific recollection as a child of looking at a picture of Neil Armstrong standing on the Moon and just thinking that's incredible. It inspired me to fly. As I grew older, I decided I would fly fighter jets, so I served as a CF-18 fighter pilot, having joined the Air Cadet Program in Canada when I was 12. Flight experience is important if you want to be an astronaut pilot: you need at least 1,000 hours pilot-in-command time in a jet aircraft. It meant, when the Canadian Space Agency asked for applications, I could put my name forward. And that's what I did.

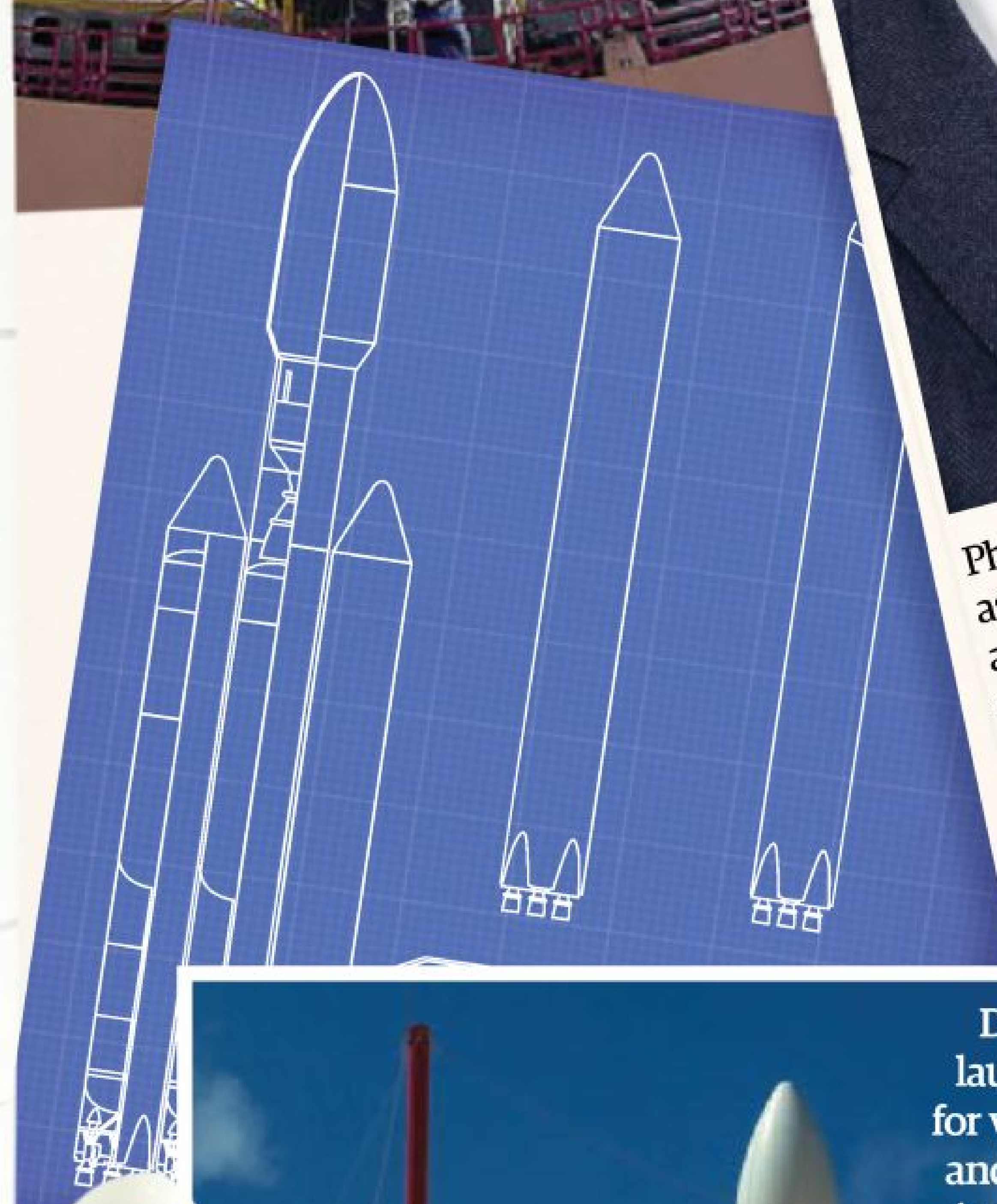
What is the training like?
JH: It's very challenging and diverse… I've been in Canada training on a robot arm recently and I'll be doing fighter jet training after that, but then I'll be back in Houston for spacewalk training. I've spent a lot of time studying languages. You need Russian to fly on Russian rockets. The list goes on and on. This past fall I went on a caving expedition where I spent a week learning how to be a caver, and then I spent the next week with five other astronauts living in a cave for an entire week, without a map, doing real science on behalf of other scientists.

Is there such a thing as a typical day?
JH: The most typical days involve systems training for the ISS. The most gruelling ones are in an enormous pressurised pool in Houston, Texas. It's a full-scale mock-up of the ISS underwater and you wear the real space suit they use for spacewalks. It simulates microgravity as best we can. You just spend an entire day in a suit going out and executing a real spacewalk plan, fixing items that have failed…

What do you need to study?
JH: We study geology because we are preparing to go beyond lower orbit. Spacecraft are being designed, techniques are being thought up, we're looking at science that we want to do on asteroids and maybe eventually on the Moon, but certainly on Mars, which is our long-term goal… A lot of this is going to be based on understanding the geology of our Solar System and trying to unravel some of the clues…

Nicolas Verstappen works on launchers for the European Space Agency

Phil Sumrall worked as a rocket scientist at NASA after a chance encounter with legendary rocket scientist, Dr Wernher von Braun, inspired him



Different types of launchers are used for various missions and the technology is constantly being improved upon

The rocket engineer

Could you be the one helping to blast the future generation of spacecraft beyond the next frontier?

BIO

Nicolas Verstappen
European Space Agency
A rocket engineer builds and tests rockets and, as such, it's a dream job for anyone who wants to be hands-on. Nicolas Verstappen is interested in launchers and in sending other people and objects into space, rather than going there himself.

CV

Fundamentals
Ensure you excel at maths and science at school.
Degree-level
Continue with a Physics or Aerospace Engineering degree.
Go the extra mile
Choose a Master's degree with a focus on aerospace.
Develop your skills
Pursue relevant internships or trainee opportunities .

Does it really take a rocket scientist to work with launchers and spacecraft? Actually, yes. Rocket engineers are involved in the creation of rockets, missiles and spacecraft, so the job requires a very particular set of skills, not least an understanding of advanced maths and engineering.

In actual fact, the job of the rocket engineer is to take knowledge from many disciplines such as maths, physics, chemistry, statics, dynamics, loads, aeronautics, flight mechanics, electricity, magnetism, thermodynamics and many others. They have to apply all this to practical systems that can transport humans and cargo into space, as well as between particular points high above Earth's surface.

This requires attention to detail, much hard graft and the ability to operate as a team. The day-to-day work involves attending technical or project meetings, taking part in design reviews and, because of the fascinating nature of the job, engaging in communication, education and public relations activities to promote whatever agency a rocket engineer works for to a wider audience. There will be lots of processes to follow and so a methodological mind with a spark of genius will stand you in good stead.

The rewards, thankfully, are potentially great. Imagine being in the position Phil Sumrall found himself in when he joined NASA in 1962. Just a year earlier President John F. Kennedy had committed the United States to landing a man on the Moon and returning him safely to Earth in that decade. "When I joined the Marshall Space Flight Center, its role in the Apollo Program was to develop the Saturn family of launch vehicles, the largest of which was the mighty Saturn V that was to enable humans to leave low Earth orbit for the first time," he tells us. "No launch vehicle of that scale had ever been designed and built before and the schedule was very tight."

Even though he was a junior member of the team, he felt the pressure to be successful and he worked very long days on the dynamics and control analyses of the Saturn V moon rocket, with each day posing a challenge. "I can't even describe the feeling that I had when Neil Armstrong stepped down on the Moon and I knew that I, along with hundreds of thousands of others, had some small part in the achievement," he says.

The greatest challenges in rocket engineering come from attempting processes that have never been done before and there is also great delight at working on technology that proves to be widely useful for all of mankind. People use the technology created by rocket engineers without even knowing it, with GPS being a particularly good example. Space applications grow and are constantly being funded, creating a challenging environment, while also offering a degree of job security.

With the rise of private space-exploration companies, the scope for employment is getting ever wider. Rocket engineers can help design and test ever more-efficient ways of getting into space. Private companies offer apprenticeships for school-leavers, giving them a great understanding of mechanical design, manufacturing and testing before they decide on a specialism.

"If you can watch a rocket fly and don't get a little choked up, there are probably other fields that you'd be better suited to pursue," says Sumrall. "It isn't the easiest way to build a career, but it has been a wonderful and rewarding life's work for me. Ultimately, I believe that it is our destiny to expand human presence into the Solar System and eventually beyond. If a person is driven to be part of that great adventure, we will need rockets to get there. No rocket engineers, no rockets!"

"If you can watch a rocket fly and don't get a little choked up, there are probably other fields that you'd be better suited to"

Insider knowledge

What got you interested in rockets?
Nicolas Verstappen: I've always been very interested in aerospace and astrophysics in general, so science is very much what I like. I remember when I was seven watching the first Belgium astronaut Dirk Frimout on television and he was a payload aboard the American space shuttle Atlantis for the Spacelab mission dedicated to NASA's Mission to Planet Earth. That was in March 1992 and that day I thought I wanted to work for space. I discovered the most efficient and interesting way to work with the space-related subjects was to become an engineer.

What do you enjoy about the job?
NV: Access to space brings many benefits and that's why I chose to become a rocket engineer. Exploration provides greater knowledge: knowledge of our Solar System, as well as better navigation and telecommunication systems. This is only possible because we have the launchers. They are capable of placing satellites accurately into space, so the benefit of space exploration has expanded in ways that could not have been envisaged so many years ago.

What would you say it takes to be a good rocket engineer?
NV: You have to be excellent in solving technical problems and you have to think of everything at the same time. You really have to rethink over and over existing solutions and sometimes you come up with a really out-of-the-box solution that's needed. If you find a solution that no one else can come up with, that simplifies a complex system, you're a good engineer.

What's the most amazing thing you've done?
NV: Europe has developed a range of launchers and has its own launch base and I think for any rocket scientist the most amazing thing is to attend the launch of the rocket you are working on. The most exciting part is the final countdown because you are so much aware of everything that could go wrong, of all the glitches that could occur. It's something very exciting. It gives you the opportunity to see concretely what you're working on and what you're working for.

The astronomers

Unlock the secrets of the universe from your desk

BIO

Jorge Vago
European Space Agency
A planetary scientist studies Solar System objects like planets, moons, comets and asteroids, looking at their history, composition and dynamics. Jorge Vago is the ESA project scientist for the ExoMars mission, preparing and co-ordinating the scientific work for the rover.

Planetary scientist

Just reading **All About Space** shows you have an inquiring mind and a keen interest in the universe, but for those who want to delve deeper, a career studying the properties and characteristics of the planets, rings and smaller bodies of our Solar System is an exciting prospect. It doesn't really matter what your initial discipline is, as long as it has some aspect of science. Once you have a PhD in the field of planetary science, you are ready to begin a career in research.

University work is challenging and adds to the body of knowledge of planets. Working for a space agency puts that knowledge to the test. There may be opportunities to get stuck in and look at proposals for rover landing sites, for example, hopefully delivering fresh research data. Engaging in workshops and discussions along with other scientists will also form a large part of your work.

Planetary scientists also look closer to home to help with research. You could be going on a geology expedition in the Australian desert, experimenting in simulated zero gravity or launching small rocket missions. Big missions will take up a lot of time and energy but they will bring big rewards.

In agencies, you will cover a broad canvas so, on a project like ExoMars, there will be various lines of research and lots of groups working in different areas from which you can draw expertise. In pure academia, you have a chance to become an expert in a particular field, however, such as a certain instrument technique. This will suit those with a passion for more specialised research.

This is the planned ExoMars rover that is set to land on Mar's surface in 2018

Jorge Vago is a planetary scientist working on the ExoMars mission that tackles fundamental questions about the planet and the possibilities that life may have existed on Mars early in its history

CV

School basics
Ensure you have a solid background in physics, maths, chemistry and possibly biology.

Degree level
Go to university and study for a degree in Physics, Astrophysics or Geophysics.

Advanced study
Complete a PhD, perhaps focusing on planetary physics or plasma physics.

Developing skills
Compete for a short-term research fellowship to gain more experience.

Research experience
Look for long-term posts in research roles.

Insider knowledge

What got you interested in the field?
Jorge Vago: I got it into my head that I wanted to be an astronaut but I grew up in Argentina and there the possibilities to become an astronaut were limited, so initially I went for engineering. The Planetary Science part came about when I finished my engineering degree and I went to the US to study more.

Is there a single path to your role?
JV: Different countries have different approaches in terms of education. For example, Italy, Spain and to a certain degree France have a broad, general approach and cover many subjects. In other countries, students concentrate early on in a certain discipline. This produces different types of scientists right out of a university. Either can be good, depending on what you want to work on.

How do you structure your day?
JV: I divide my day between responding to a gazillion emails related to the project and working on certain more-scientific aspects. For example, one of the big things this year is the landing site selection for the 2018 ExoMars Rover mission. Another chunk of time, around 10 to 20 per cent, goes into following what the project team does in terms of mission development. This involves discussing mission design details with the project manager and managers of the various elements in the mission. There's very little time left for what you might call actual research or creative stuff.

What would you say your job is?
JV: The job of project scientist is to act as a link or nexus between the scientific community working in the mission and the project team implementing the mission. The scientists want to be sure they're in a position to do great science with the mission and they're choosy in what they want and very specific, but the project has to deliver technical excellence on time and within the given budget. For this they rely on a large industrial team, of many tens of companies and providers whose work they need to co-ordinate. The project scientist has a very difficult job.

What's your greatest achievement?
JV: Professionally, the greatest thing I'll ever do will be to land the Rover on Mars and start drilling. If we can find organic molecules in the sub-surface, that would be the most amazing thing, so that one is yet to come.

The Herschel Space Observatory with a stellar nursery in Aquila, the Eagle

Pilbratt says Herschel will bring a big step forward in our understanding of how stars and galaxies form and evolve

The European rocket Ariane 5 containing the Herschel and Planck satellites

CV

Extra lessons
Sign up for science and advanced maths courses at school and college.

Degree level
Apply for a degree course in Astrophysics at a reputable university.

Advanced study
Continue in academia and complete a Master's degree.

PhD-level studies
Stay on and study for your PhD, engaging in high-level research. You should then begin a post-doctoral research job in academia or with a space agency.

Astrophysicist

BIO

Göran Pilbratt
European Space Agency
Astrophysicists apply the laws of physics to understand the workings of the universe. They observe galaxies, planets, exoplanets and stars. The term astrophysics can encompass many disciplines, including mechanics, relativity, nuclear and particle physics. Herschel project scientist Göran Pilbratt from ESA looks at how stars and galaxies form and evolve.

Have you ever gazed at the stars, yet sought not to merely view but understand them? Astrophysics lets you delve into how the universe works, enabling you to explore how it began and changed over time.

Although their discipline falls under astronomy, astrophysicists study everything outside of the Solar System, whereas planetary scientists tend to study everything within it.

Astrophysicists look at the physics of the universe and how objects within it interact either by coming up with theories or testing them using computer simulations. They benefit from huge and expensive projects such as NASA's Hubble Space Telescope, the Chandra X-ray Observatory, the Spitzer Space Telescope, ESA's Herschel Space Observatory, the XMM-Newton X-ray observatory and INTEGRAL, the International Gamma-Ray Astrophysics Laboratory. Each of these enables a lot of further-reaching insights into the mysteries of space.

University is a perfect place for an astrophysicist to start – here you'll be able to conduct research spanning large time and length scales, study black holes or gain a deeper understanding of dark matter, astroparticle physics or cosmic microwave background radiation.

One thing is for sure, it's not easy, nor can you quickly build up expertise. It can take up to a decade after leaving school to accumulate the knowledge you need and it's for this reason that astrophysicists tend to stay in their jobs for a long time – with few vacancies. If you like the idea of a role in research and spending the bulk of your time trying to find fresh insights that explain astrophysical phenomena, this is the area for you.

Insider knowledge

When did you become interested in the field?
Göran Pilbratt: It's actually something I've been interested in since I was a child but I was never what sometimes is referred to as an amateur astronomer – I was more into physics...

How did you start working for the ESA?
GP: When you work for a PhD, the standard career path is a fellowship in a university somewhere to continue the research. That was my plan but one of those opportunities was a Post-Doc here at the European Space Research and Technology Centre in Noordwijk, the Netherlands.

What sort of projects do you work on?
GP: I'm a project scientist for a space observatory called Herschel... It's my job to represent and be an advocate of the science to be done by a project and to maximise the science return of a mission in every respect. Early on in the mission, for instance when you're building a spacecraft, that means safeguarding the important requirements of doing science. This can be everything from instruments and temperatures to the size of telescope. When you actually start building something, you start to realise that the mass is too high or the power consumption is too high or whatever, and engineers will want to cut corners and decrease requirements. It is up to a person in my position to defend the requirements that are important for science.

Does your role change during the mission?
GP: The priority is to use the observatory in the best possible way. This is broad and includes many things, for instance by providing information and tools to astronomers to prepare observations, getting the observations executed and providing the resulting data and tools for data-processing and analysis. There's always interaction with people and various committees, such as science teams, time-allocation committees and the astronomers themselves.

Spacecraft operations manager Nic Mardle standing on console with flight team members

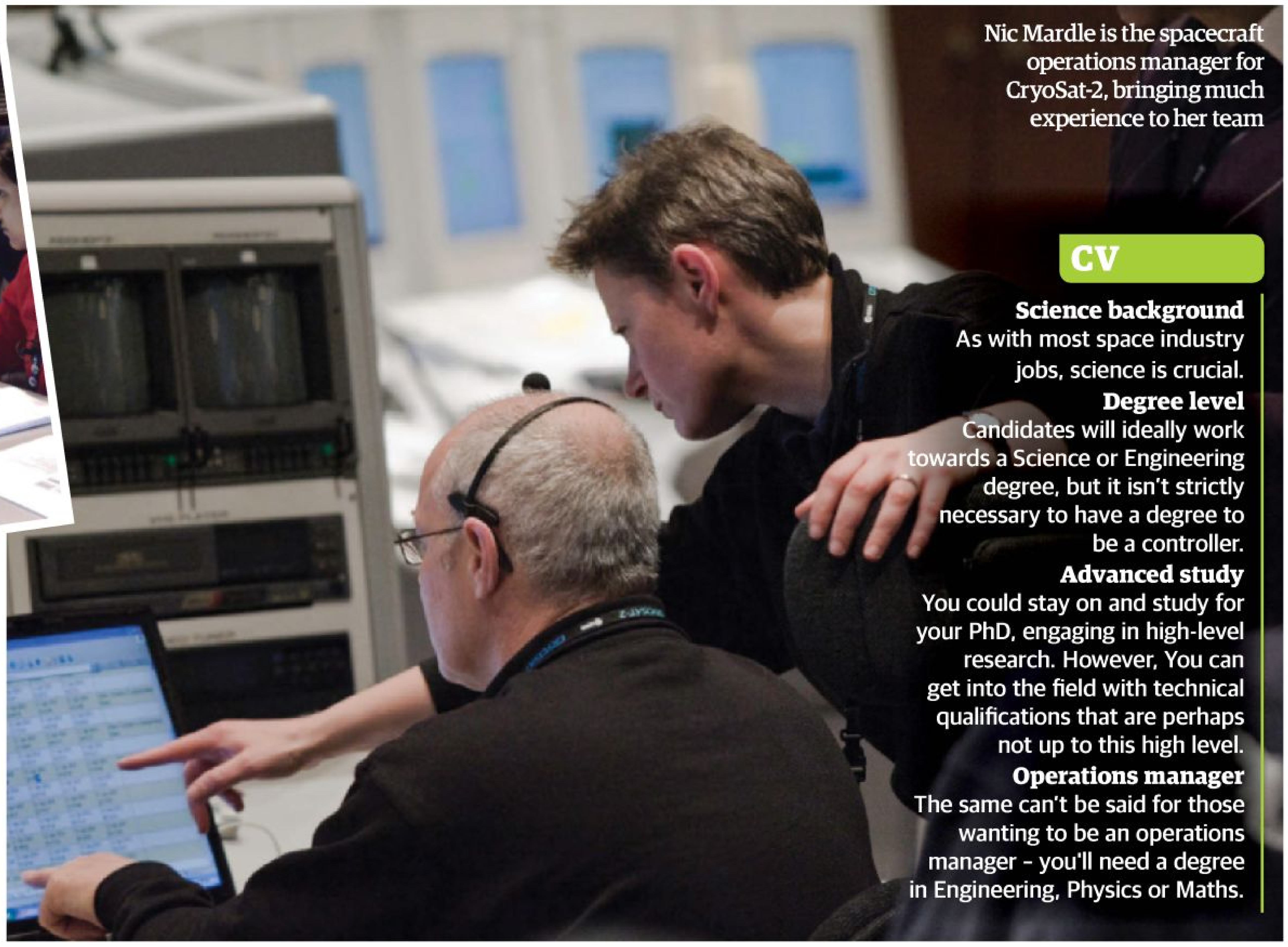
Insider knowledge

What got you interested in spacecraft operations?
Nic Mardle: I was originally a sponsored student at British Aerospace in Stevenage before I went to university to study Aerospace Systems. I went back to British Aerospace, working in the Assembly Integrations Verification area, where we put spacecraft together, testing and launching them...

Is there a path to that job or do you just need experience?
NM: Operations isn't something that you learn at university. You can learn the engineering or the physics side of it but operations is very specific. Common sense and an engineering background works well. You must learn about each spacecraft individually, how it works, what the constraints are, how it interacts with the ground segment, all these things that they simply can't teach you.

What's your typical day like?
NM: It can be making sure the inputs and outputs are ready for the next weeks of operations. It might be planning for special operations – there are a number that we have to do, whether it's as simple as an orbit manoeuvre or a role campaign that we might do to support scientists on the ground, as well as calibrations of the instrument, or perhaps we have to make a recovery of something.

What would you say are the challenges in building a flight control team?
NM: You have to find people who can work together. We have lots of interactions with different teams so the people who make up a core team have to trust one another and work well together.



Nic Mardle is the spacecraft operations manager for CryoSat-2, bringing much experience to her team

CV

Science background
As with most space industry jobs, science is crucial.

Degree level
Candidates will ideally work towards a Science or Engineering degree, but it isn't strictly necessary to have a degree to be a controller.

Advanced study
You could stay on and study for your PhD, engaging in high-level research. However, You can get into the field with technical qualifications that are perhaps not up to this high level.

Operations manager
The same can't be said for those wanting to be an operations manager – you'll need a degree in Engineering, Physics or Maths.

The mission controller

Could you be the glue that holds an entire mission together?

BIO

Nic Mardle
European Space Agency
As a spacecraft operations manager for the ESA, Nic Mardle works on the CryoSat-2 research satellite, ensuring it's properly controlled. The satellite provides scientists with data on Earth's polar ice caps, tracking changes in the ice's thickness. It's one of the many roles within the industry and shows the importance of monitoring our own planet.

Mission controllers look after the progress of a satellite or spacecraft sent into orbit. They will initially communicate with it from the main control room before operations switch to dedicated control rooms that are smaller and more tailored for each task. For the European Space Agency, much of this takes place at the European Space Operations Centre in Darmstadt, Germany.

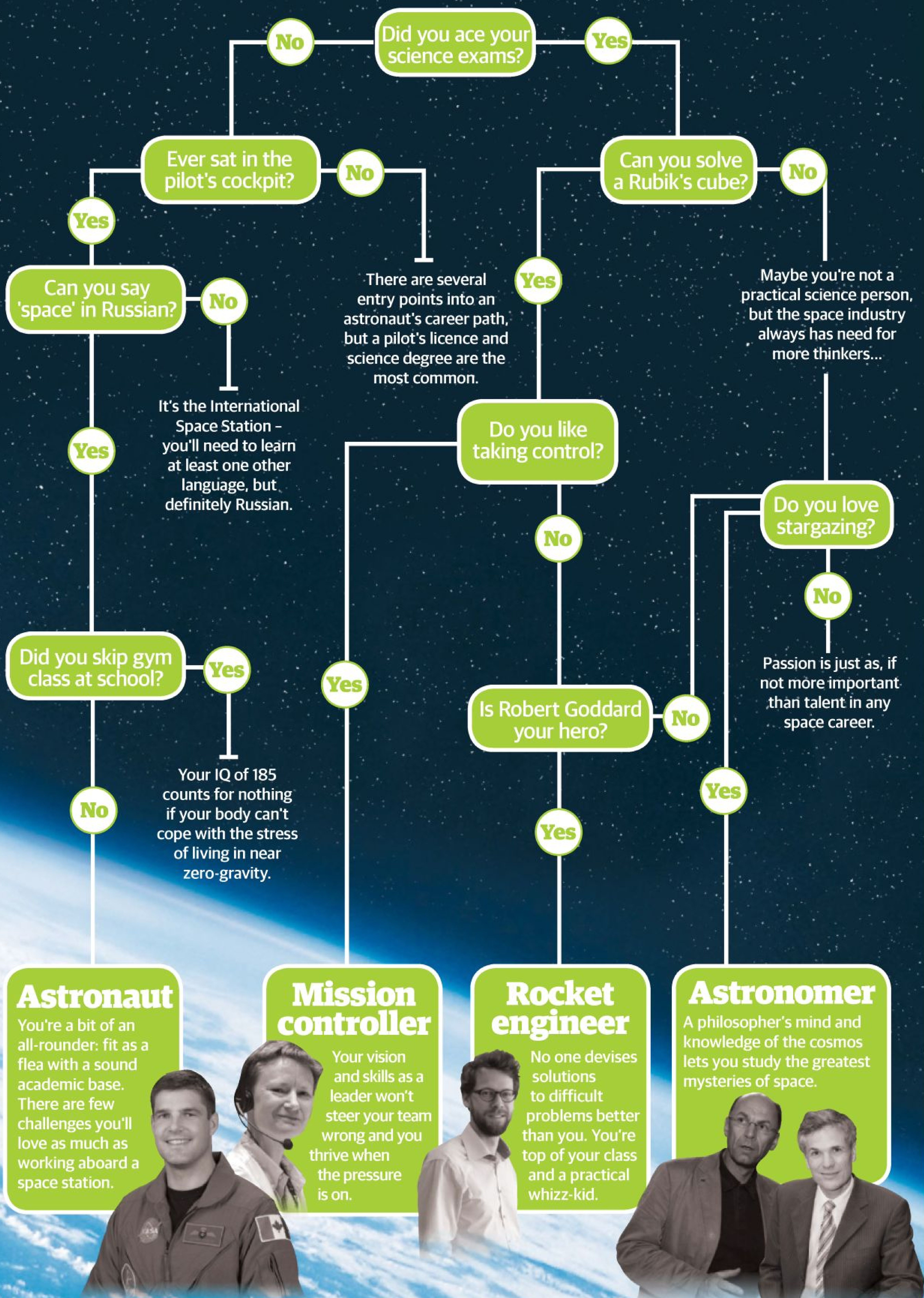
A mission controller is very much at the coal face, interacting on a daily basis with the spacecraft, sending commands, checking the telemetry, making sure that all of the day-to-day processes happen properly and then reacting first when something happens. They oversee various sets of teams, each with different responsibilities such as sub-system and system engineers who may look after the sub-system on a spacecraft or part of the ground segment, lending expertise in a certain area.

Nic Mardle's role as a spacecraft operations manager may see her planning for special operations. She may have to prepare and develop ground segments and constantly have an eye on the future, reading documents to see how something is set up and advancing on it or devising evolutionary plans.

Working in mission control is a constant learning experience. Even though a spacecraft is designed in a certain way, no one can know everything about it so, when something happens, there is a need to learn something new and this could be a completely new sub-system.

The type of people who would enjoy operations are those who like variety and who prefer to feel they're interacting with a spacecraft, rather than working with paper documents and theories. Mission controllers fly spacecraft on a day-to-day basis, sending commands to alter its orbit or altitude, and while they don't touch the spacecraft itself, they monitor the on-board instruments and keep a watch to ensure everything is working properly. This makes the job more applied and less theoretical than a simple design position.

Which space career is right for you?



Five weird space jobs

Chief sniffer

'Nasalnaut' George Aldrich spends his days at NASA smelling the various items that are sent into space. Whether it's a spacesuit, pens, toys, or even adult nappies, he gives them a good sniff to ensure unpleasant odours that intensify in space do not pose health risks for the astronauts.

Tour guide

Perhaps one day you will be uttering, "And to your left, there is Jupiter", since a UK government-backed report in 2010 suggested potential future careers as space tour guides will become available. With the rise in private space companies such as SpaceX, space tourism is set to take off massively.

Space shrink

Being confined in a small space with only a few people miles away from the comforts of Earth can be a burden for astronauts, so it's vital their mental health is monitored and assessed. Space psychologists support crews and help them to cope with isolation and potential boredom.

General helper

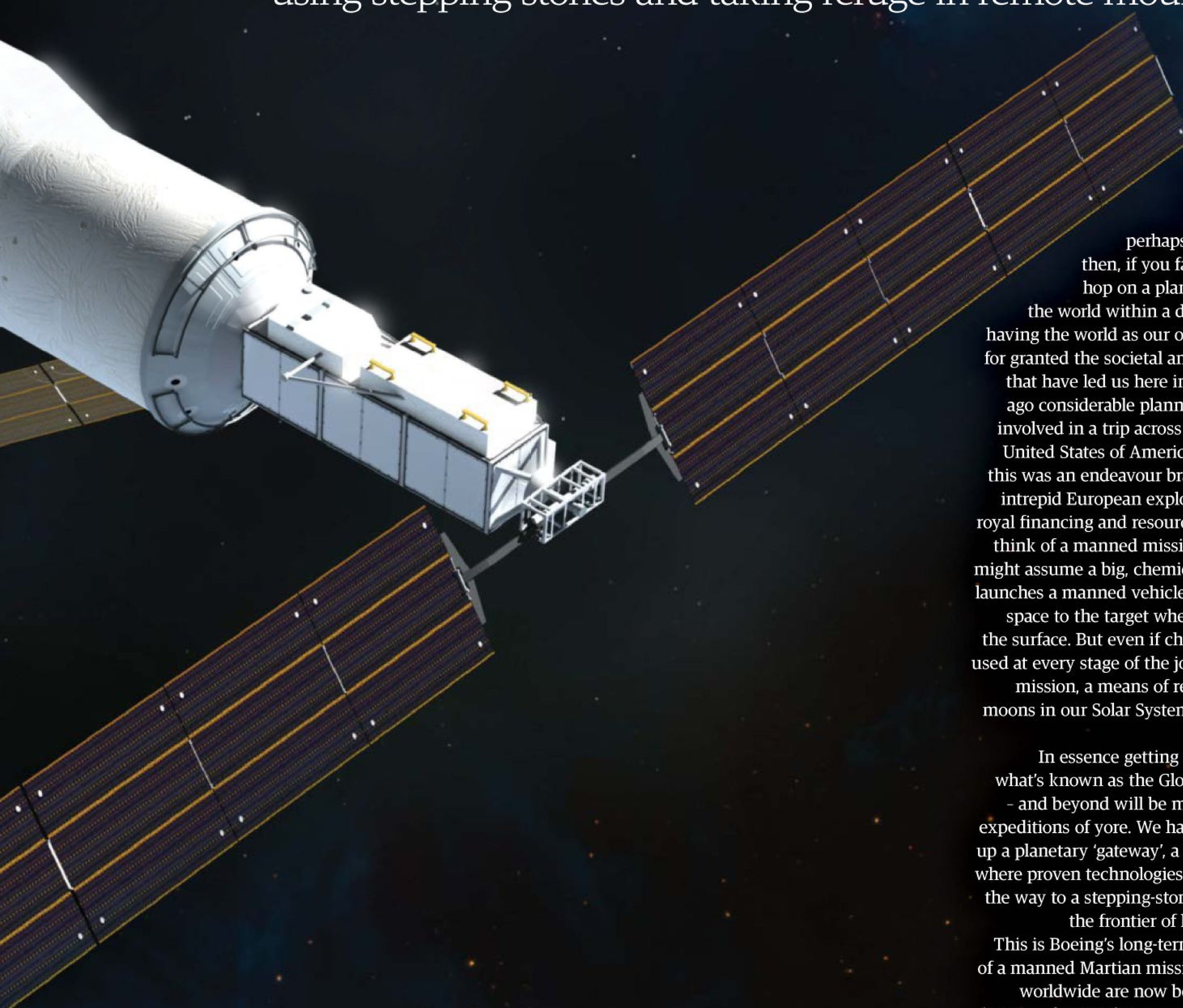
This caretaker role advertised at SpaceX has the successful candidate driving forklift trucks, cleaning up work areas and moving heavy equipment as well as "miscellaneous tasks as directed". Being "willing to do anything" is a requirement of this wide-ranging role, but it needs a whole set of skills from plumbing to carpentry.

Visual co-ordinator

Every space HQ needs to look nice, so if you fancy selecting furniture, choosing the colour of paint for the walls and ensuring everything works in visual harmony, then this would be the perfect role for you. After all, we wouldn't want space industry experts to be put off by clashing wallpaper and upholstery.

DEEP SPACE EXPLORATION

It's humankind's 'final frontier' but space is too big for us to conquer all in one go. **All About Space** speaks to Boeing's Michael Raftery on building gateways, using stepping stones and taking refuge in remote mountain cabins



Today, your next nearest city might be just a short drive away; a few hours, perhaps, to the next country and then, if you fancied it, you could easily hop on a plane and be on other side of the world within a day or so. We're so used to having the world as our oyster that it's easy to take for granted the societal and technological advances that have led us here in the first place: a century ago considerable planning, money and time was involved in a trip across the Atlantic Ocean to the United States of America. Half a millennium ago, this was an endeavour braved only by a handful of intrepid European explorers who were backed by royal financing and resources. So when most people think of a manned mission to another planet they might assume a big, chemical rocket is involved that launches a manned vehicle out of Earth orbit, across space to the target where a lander is deployed to the surface. But even if chemical rockets were to be used at every stage of the journey that's an endgame mission, a means of reaching other planets and moons in our Solar System for many generations in the future.

In essence getting to Mars – the final step in what's known as the Global Exploration Roadmap – and beyond will be much more like the furtive expeditions of yore. We have to scout ahead and set up a planetary 'gateway', a sort of deep space station where proven technologies and techniques can pave the way to a stepping-stone approach to expanding the frontier of human space exploration.

This is Boeing's long-term solution to the problem of a manned Martian mission, which space agencies worldwide are now beginning to focus on. The director of ISS Utilization and Exploration at Boeing,

Michael Raftery, thinks that effective technology and infrastructure is only part of this complex equation.

"The first thing that's important to say is that the idea of a gateway is to leverage the partnership that we've built with the ISS. So it's as much about the management model as it is about the technology. That's really important. So what we're proposing and promoting is that this be an international programme, that the hardware be sourced from international sources and it's not a US-centric programme. The gateway itself will be much smaller than the ISS and we probably wouldn't have it manned all the time. We call that 'man-tended': people would be there only when they're there to do a mission of some kind, but most of the time there wouldn't be people there.

"The reason is that we aren't trying to re-create a space station to deep space – that really isn't what we're doing. You need to think of this as more like a cabin in the mountains that hikers might stop at, to store some food and if there was a bad storm you might duck inside the cabin. It's more like that than the ISS is today. The ISS is a big research facility, it's like a giant laboratory in the sky. The gateway is more of an outpost that would be used to support missions to the surface of the Moon, an asteroid or to Mars."

Boeing's proposal is to build on what's been established with the International Space Station and create a platform for exploration that's situated way beyond the ISS's 370-kilometre (230-mile) low Earth orbit, out at one of the Earth-Moon L1 or L2 Lagrange points, which are also known as libration systems. At an altitude of over 1.5 million kilometres (932,000 miles) from the Earth, this gateway could serve a myriad of purposes: facilitating future missions to other planets and moons, servicing space observatories, forming a platform for the capture and investigation of near-Earth asteroids and becoming a vital refuelling and maintenance waypoint in forthcoming missions to the Moon and Mars.

This concept of a cislunar gateway would be directed and maintained by established ISS control centres and infrastructure. The platform could easily support future manned lunar missions by providing a conveniently proximate docking platform that would allow longer mission durations and more time for vital research. There's also a cool piece of technology that would result directly from a gateway of this type: a reuseable lunar lander. The exploration platform could form the base for a small and relatively cheap lander moving to and from the surface of the Moon, to be refuelled and repaired in time for the next mission by a team of astronauts temporarily living in the platform habitat. Considering that the total cost of the first of six discarded Apollo lunar modules was reported to be $350 million (£213 million) in 1962 (over $2.7 billion/£1.6 billion today), the prospect of Boeing's exploration platform has to be quite attractive to any Moon-bound space agency, for this reason alone.

"The idea behind an exploration platform for a gateway," continues Raftery, "is really about having a place that can be used for different kinds of missions in deep space. So the ISS is in low Earth orbit that, if you think about it in terms of energy or propellant and we're about two thirds of the way into deep space when you're in LEO... you're still a whole other third to go. That distance is quite a bit when you're dealing with rockets and rocket propellant, things like that. So the idea is that most of the missions we're planning to do in the future that involve going to destinations like the Moon, an asteroid or Mars, you have to go into deep space. Having a place that would be like a jumping-off point for those missions."

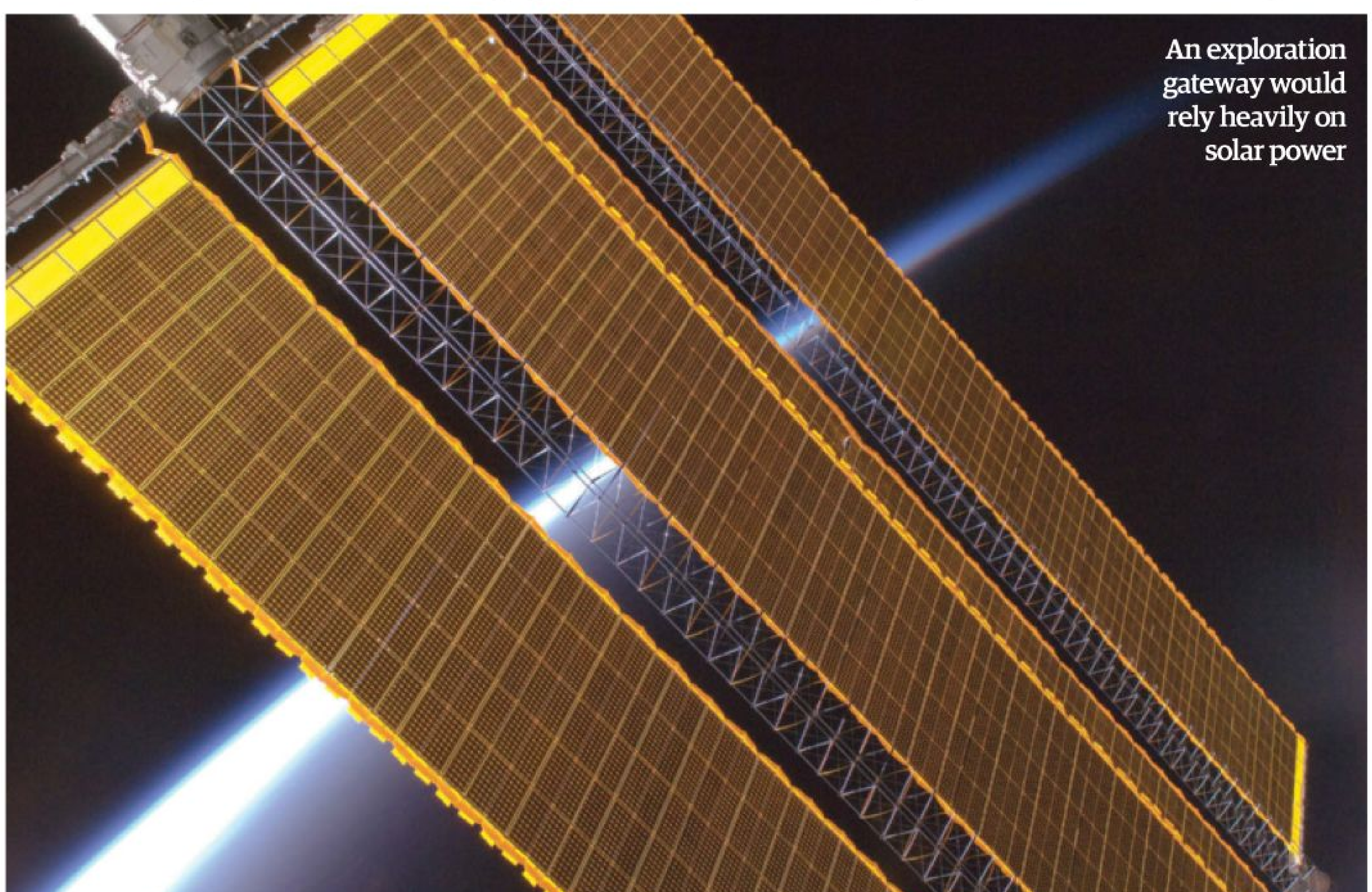
One of the big advantages of this gateway that directly benefits high-profile missions running today is its potential use for space observatory repair, maintenance and upgrades. Hubble itself has been repaired and upgraded by no less than five separate service missions, with a launch for each, some of which required multiple EVAs (extravehicular activities – work that required an astronaut leaving their spacecraft) and total costs for all five missions that ran into the billions of dollars. All of this, for a telescope that's in low Earth orbit. The efficiency of having a libration system platform would reduce the cost of servicing space telescopes and more besides.

"I think a key benefit is for telescopes," Raftery tells us. "All of our really large, new observatory-class telescopes are going to end up going out into the libration system. I think Hubble is the last big telescope we're going to put into LEO. If you look at the James Webb Space Telescope and the big telescopes of the future, the plan is to put them in Sun-Earth libration point number two. This is a different libration point, it's part of the Earth-Sun system, as opposed to the Earth-Moon system. But once you're in this libration system you can move around easily without using a lot of fuel. So having a place where you can base a crew, where you can do a repair mission (like we did with the Hubble telescope) to make these observatories last and extend their life... it's something that's extremely valuable. These things are really expensive and they have very high science returns, so you want to keep them alive as long as you can."

"You need to think of this as a cabin in the mountains... if there was a bad storm you might duck inside it"


The new Orion spacecraft is used in Boeing's proposal


Orion is still in progress but its test launch is in September


An exploration gateway would rely heavily on solar power

Gateway to deep space

The first step to human expansion into the Solar System? Place an exploration platform in space over a million kilometres from Earth

Taking advantage of gravity

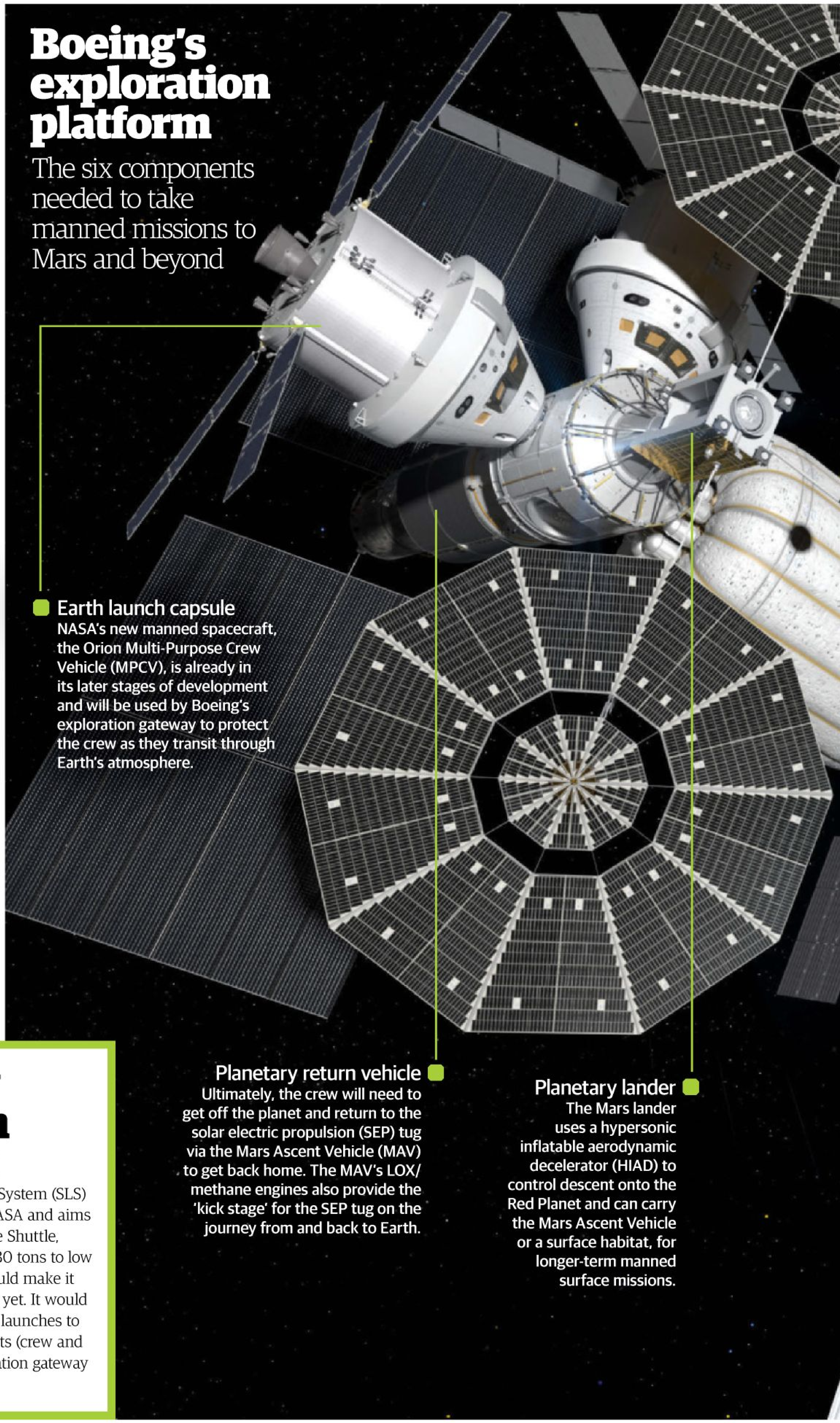
Libration systems are important, but they're not simply convenient regions of space where we can dump probes, telescopes and future exploration platforms. These are high-energy systems far beyond the gravity wells of the Earth and the Moon where gravitational forces are balanced. The Sun-Earth libration systems L1 and L2 have been used for missions like the Herschel and Planck space observatories, and will be used as the final destination for the billion star-surveyor Gaia (which launched in December 2013) and the near-future James Webb Space Telescope. Spacecraft don't really go to these systems, they orbit them and once there they can move around freely, into other libration systems or orbits in a similarly high-energy state. Critically, they can do this without using very much energy at all, so sustainable, efficient and cost-effective propulsion systems that rely on solar energy come into their own here - exactly what Boeing has in mind with its own exploration platform proposal.

While chemical rockets are the most practical solution that exists for getting the modules of an exploration gateway off Earth and into space, once it's been assembled and is orbiting a libration system, it's a very costly and inefficient way of moving around. Even the best chemical rockets in their class, such as the RL-10 that has been flying in various forms since it first launched in the early-Sixties, are based on old technology. We can work on the manufacturing process to make them cheaper to build but, ultimately, the science doesn't change.

"If you look at what's going on with SpaceX, they're revolutionising the way that rockets are built by mass producing them and applying modern manufacturing techniques. This trend is going to continue worldwide, you're going to see a lot of companies adopting the same kind of philosophy once the launch costs come down. What will happen in the future is that we'll have to move towards a more efficient kind of propulsion and the answer is really electric. I think what you're going to find is that solar electric propulsion is much more prevalent and popular in the future because it's almost an order of magnitude more efficient. But it's a different kind of propulsion: chemically you have high thrust and short duration, with electric you have low thrust and very long duration. So you have to get out of the gravity well and then electric propulsion really rules."

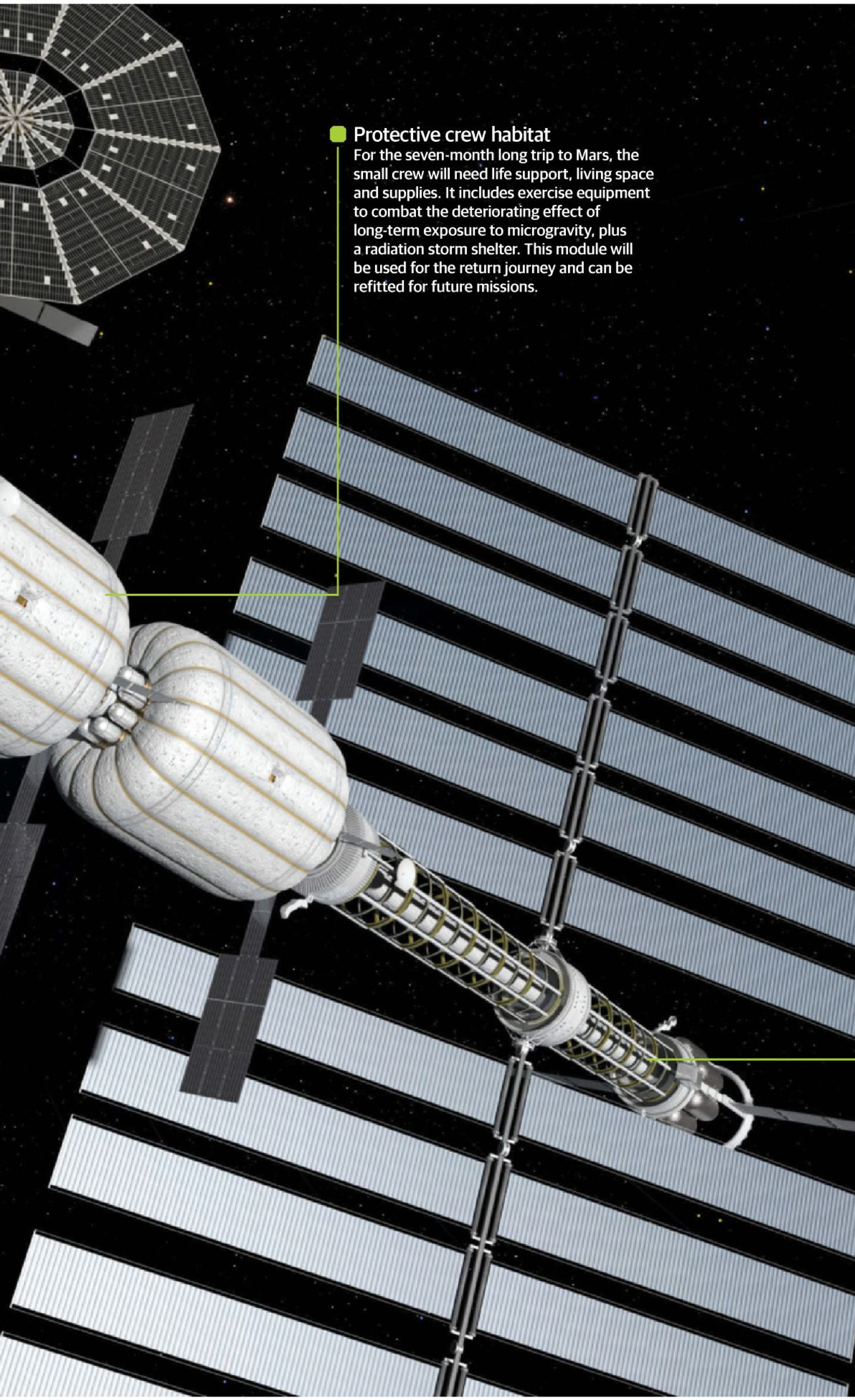
Boeing itself already has an 'all-electric concept' satellite called the 702SP in the pipeline, that differs from its predecessors in that it ditches the chemical part of its propulsion system completely in favour of solar electric power. This minimises its launch mass by losing the rocket engine and fuel propellant, to increase payload and make it a more energy-efficient craft. The 702SP operates up to a medium power range of around eight kilowatts, but part of Boeing's gateway proposal is a solar electric propulsion system with much greater ambitions. "That's the beginning of a trend," Raftery explains. "These satellites will get bigger and bigger and the systems will get bigger and bigger. All we'll need to do is make a bigger solar array so you'll have more power. If you take the solar arrays on the ISS for example and used them, they'd be about a megawatt. A megawatt solar electric system – that's what we'd need for Mars."

Aligning its exploration gateway with the Global Exploration Roadmap, Boeing is looking to facilitate



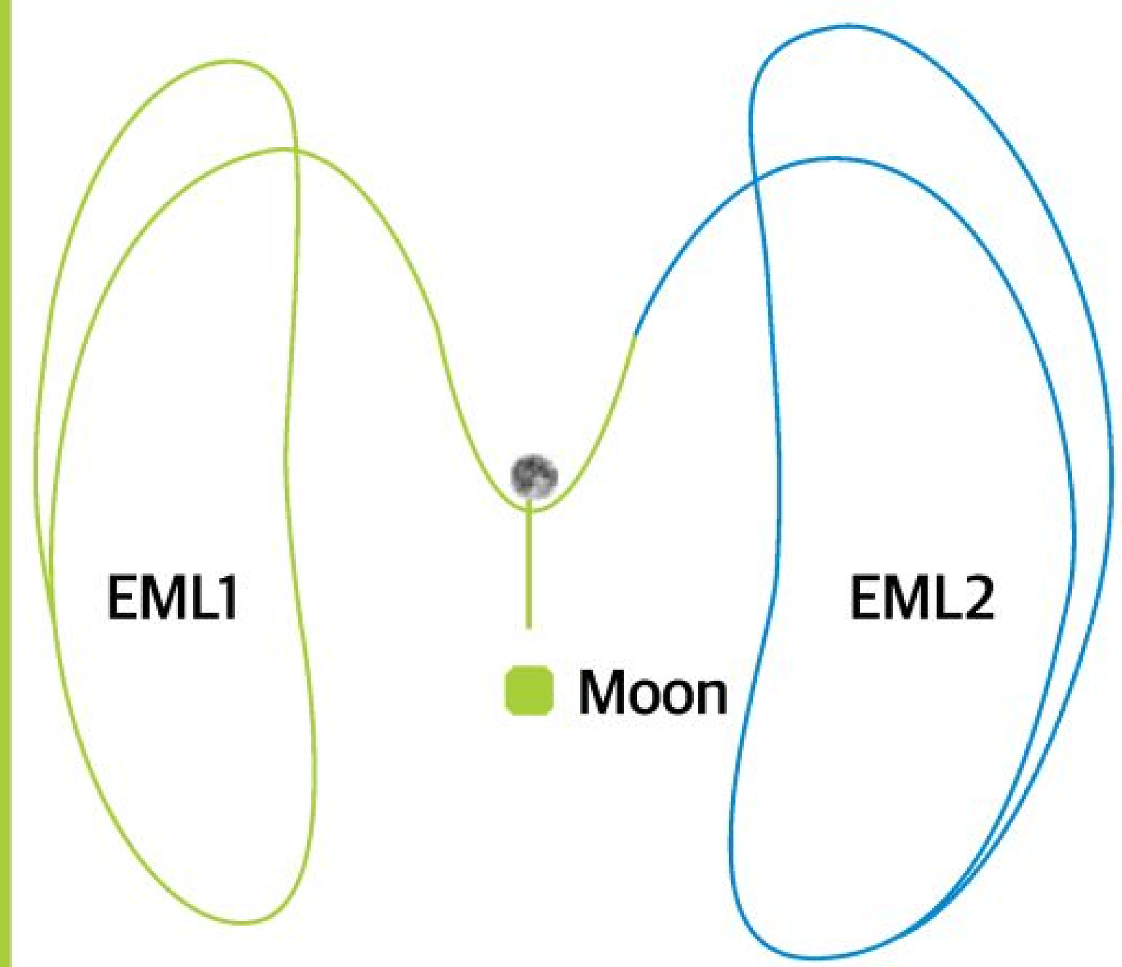
Heavy launch rocket

The Space Launch System (SLS) is in progress by NASA and aims to replace the Space Shuttle, with a payload of 130 tons to low Earth orbit that would make it the best lift vehicle yet. It would still require several launches to take the components (crew and cargo) of an exploration gateway into space.



Protective crew habitat

For the seven-month long trip to Mars, the small crew will need life support, living space and supplies. It includes exercise equipment to combat the deteriorating effect of long-term exposure to microgravity, plus a radiation storm shelter. This module will be used for the return journey and can be refitted for future missions.



Relocating orbits

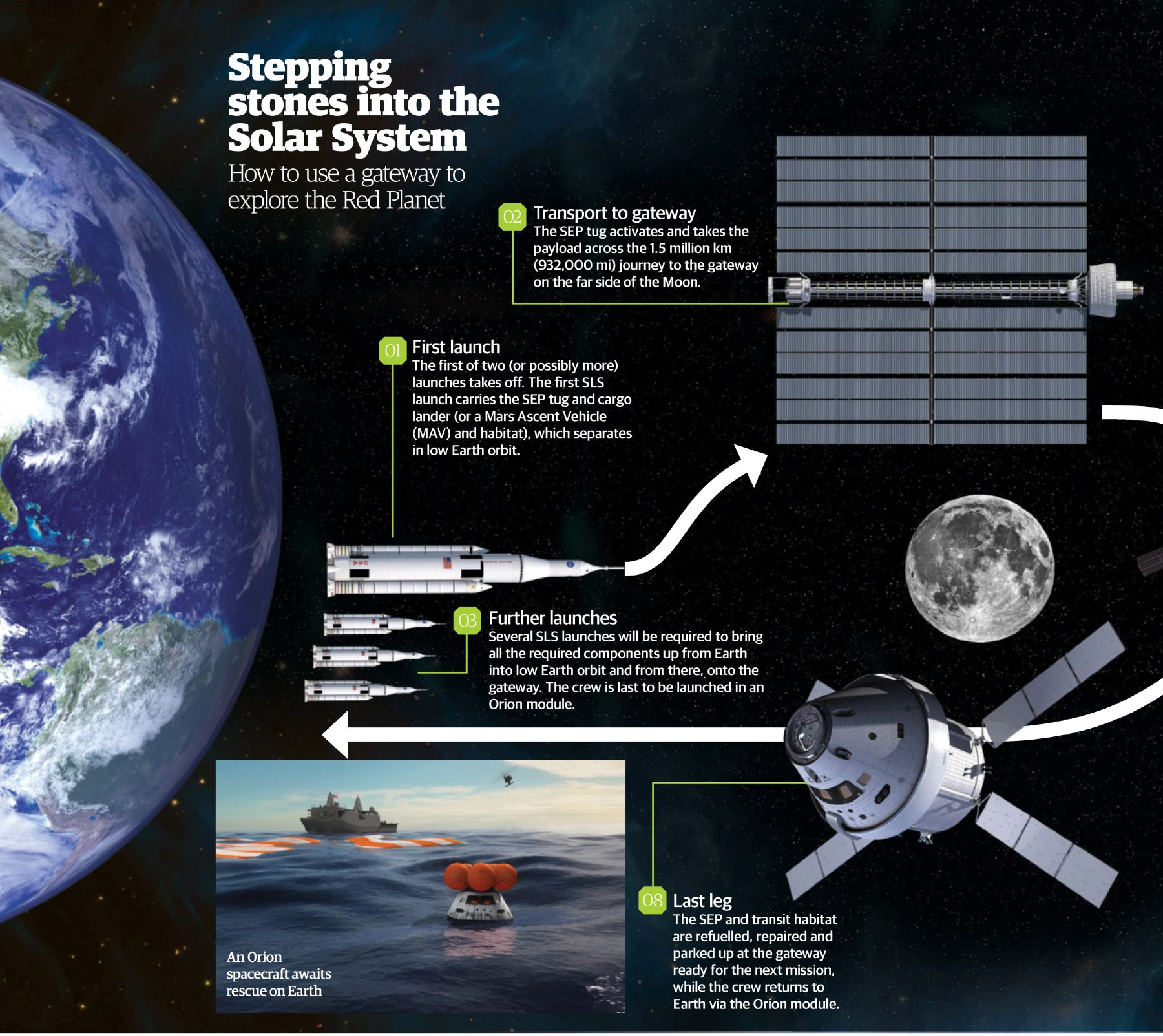
While both Earth-Moon libration systems are appropriate for a gateway and the platform will be capable of moving between the two, EML2 on the far side of the Moon is currently the preferred location for the near future. This libration system will reduce the propellant requirements for the Orion module, plus there are many more far-side missions that are of interest to the worldwide space community. Relocation will occur frequently during the lifetime of the platform and could involve dropping a lunar lander off onto the surface of the Moon while transitioning through lunar orbit to the opposite libration system.

Long-distance spacecraft

One of the major components of the exploration gateway is the solar electric propulsion (SEP) tug. This is an energy-efficient ferry from Earth to Mars, with 30 thrusters supplying 50 kilowatts of power for a total of 1,500 kilowatts of power at one astronomical unit. The SEP portion carries a tank with krypton propellant, which supplies a 'kick stage' that will be used to halve the time a dangerous manned trip to Mars would take, to 256 days.

Stepping stones into the Solar System

How to use a gateway to explore the Red Planet



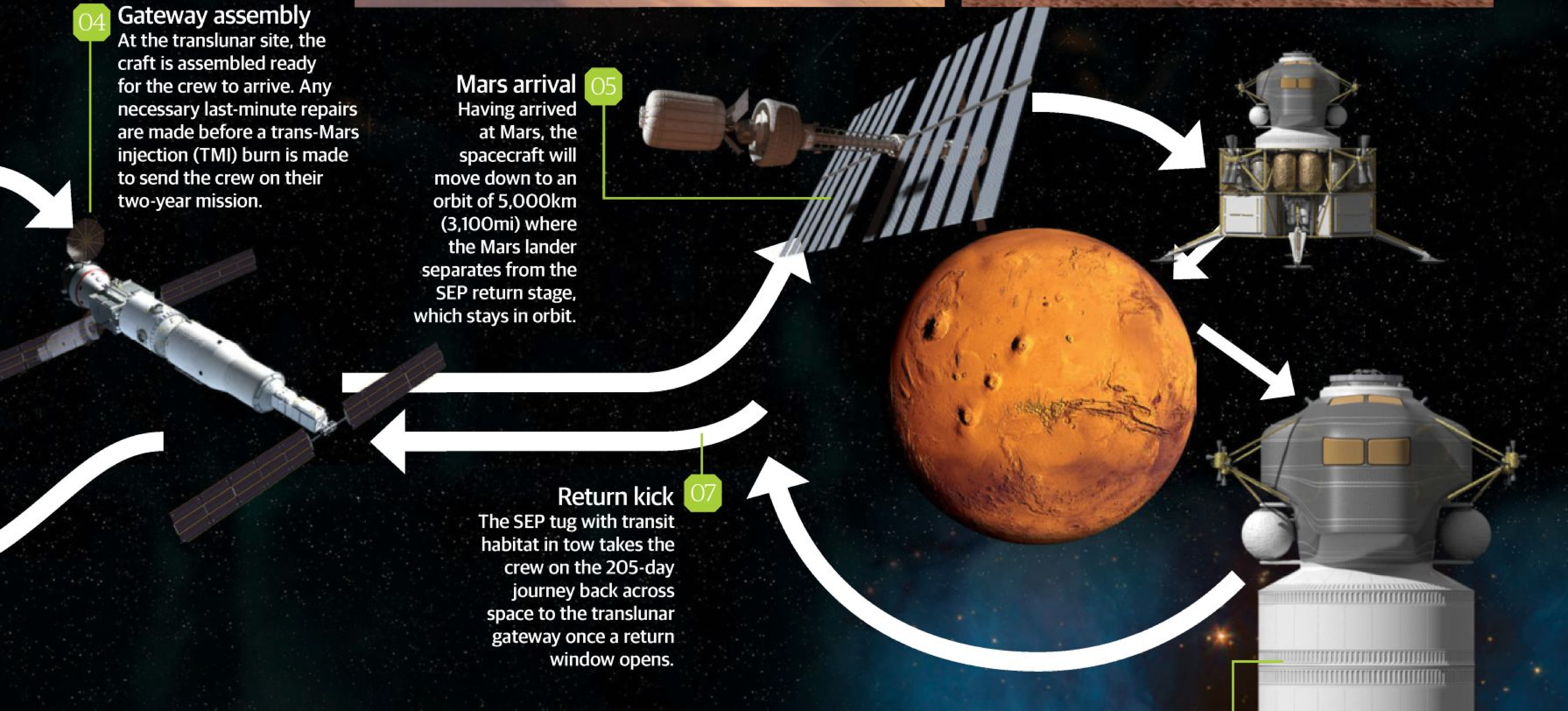
An Orion spacecraft awaits rescue on Earth

a mid-2030s manned mission to Mars. Here, a spacecraft would be brought up to space in several pieces by a number of launches on NASA's upcoming Space Launch System. It would then be assembled on Boeing's cislunar gateway and the final touches put to the spacecraft, making repairs to components that might have broken during launch or on the way to the libration system. Raftery doesn't think this gateway will grow once it's been established, though – not like the ISS has over the years, anyway. "I doubt that the cabin in the mountains will get much bigger," he says. "It will really depend on how these large spacecraft are put together. For instance, if you were to use this as a place to go to the Moon regularly – let's say the nation decides it wants to build some infrastructure on the Moon on the far side, a big radio telescope – then you might reuse your lunar landers. And if you did that, you might base them at this place. Because it gives you a place to reuse, refuel and refurbish them... It would all depend on what path exploration takes. A lot of the people in the community right now are working on how we're going to send people to Mars. And I think what you'll find is that it's likely we'll have to build spacecraft to make that happen and you're not going to launch them all at once, you're going to launch multiple pieces. The reason you'd do that is because out there, you're all the way out of the Earth's gravity

> "Say the nation wants to build a big radio telescope on the far side of the Moon... you might reuse your lunar landers"

The manned Mars lander with heat shield on atmospheric entry

A manned mission requires a habitat for the duration of the mission

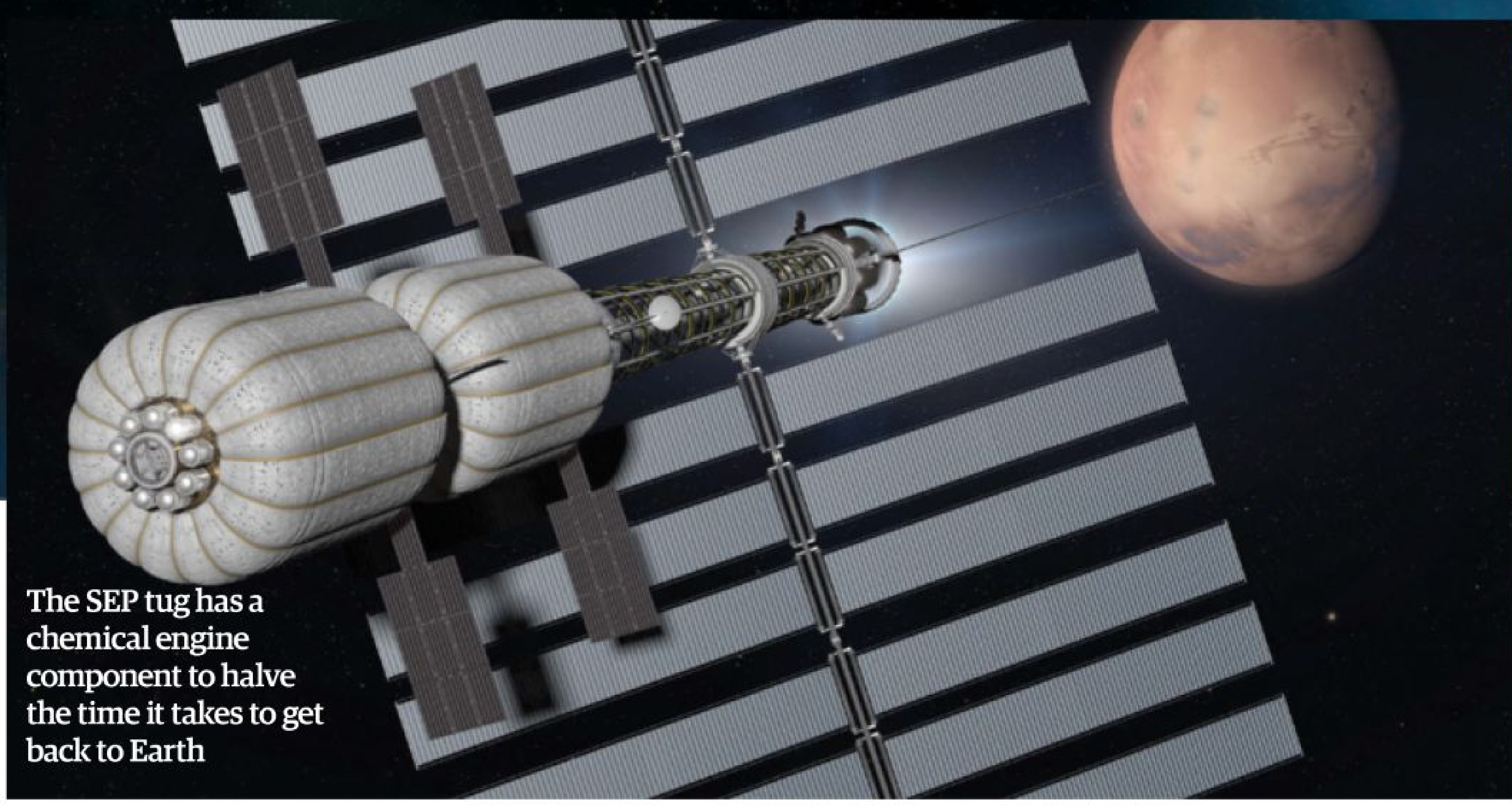


04 Gateway assembly
At the translunar site, the craft is assembled ready for the crew to arrive. Any necessary last-minute repairs are made before a trans-Mars injection (TMI) burn is made to send the crew on their two-year mission.

05 Mars arrival
Having arrived at Mars, the spacecraft will move down to an orbit of 5,000km (3,100mi) where the Mars lander separates from the SEP return stage, which stays in orbit.

06 Leaving Mars
After the crew has completed their mission on Mars, they use the MAV to return to the SEP tug awaiting them in orbit.

07 Return kick
The SEP tug with transit habitat in tow takes the crew on the 205-day journey back across space to the translunar gateway once a return window opens.



The SEP tug has a chemical engine component to halve the time it takes to get back to Earth

well. If you try to do it in LEO, you're going to end up having to do some big chemical burns to get out of there, which runs the risk of something breaking. So we're looking at the gateway as a way of having somewhere to assemble these spacecraft."

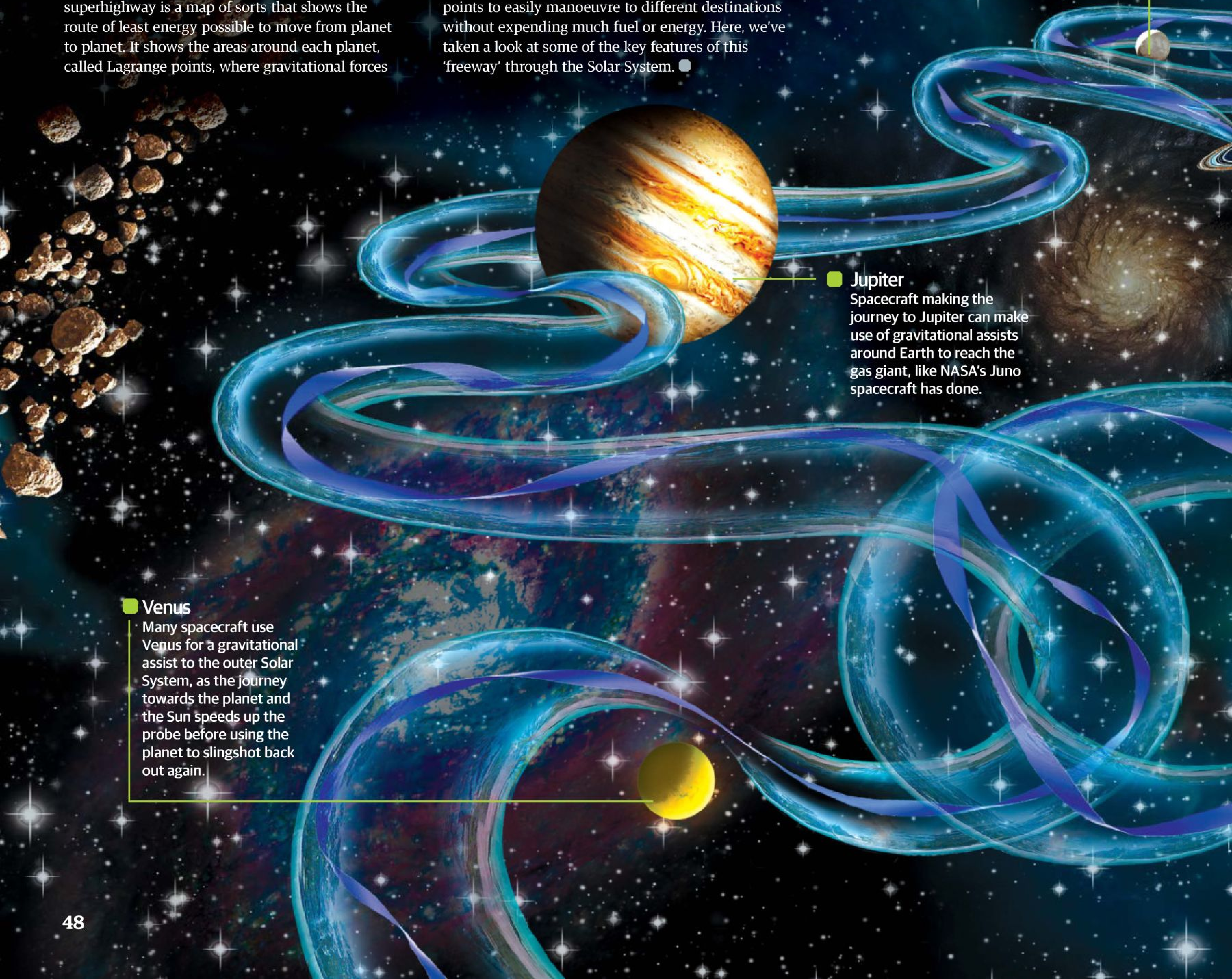
If Boeing's concept is made reality, Raftery thinks the future of human exploration and expansion into the Solar System and beyond would take a distinct pattern. "It's just like anything with migration in humans," he says. "If you think about how over the millennia humans have moved from place to place, they will often establish a beachhead or some kind of an outpost as a first step. Then they expand that and establish another one. So you can imagine an outpost, maybe in the orbit of Mars, being the next logical step. You would then go from one to the next, then to the surface and then your outpost would be on the surface of Mars. Then the orbit of Jupiter, onto Titan or one of the moons."

From there it doesn't take a big stretch of the imagination to see how we might eventually expand, explore and even colonise parts of our Solar System. We could enable difficult missions in the concept phase like the subsurface Europa probe, more easily study the outer planets Neptune or Pluto and create a network of gateways and outposts that might one day, with the right technology, even facilitate a mission to another star.

Interplanetary superhighway

How spacecraft can use gravity, or lack thereof, to hitchhike through the Solar System

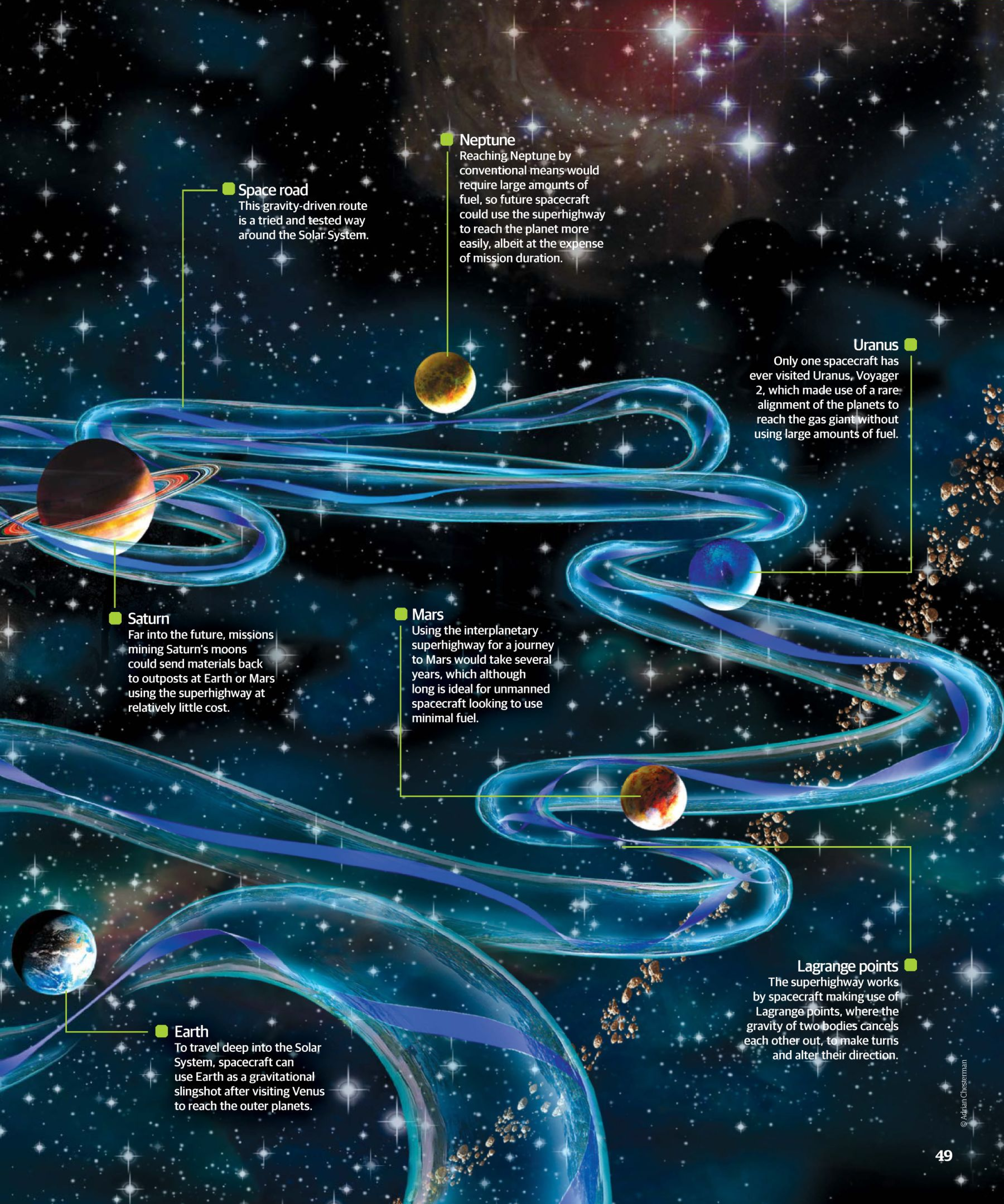
If you're planning to send a spacecraft from Earth to another part of the Solar System, it might be a good idea to study your galactic road map first in order to find the best route possible. The interplanetary superhighway is a map of sorts that shows the route of least energy possible to move from planet to planet. It shows the areas around each planet, called Lagrange points, where gravitational forces balance, therefore making it easy for a probe to turn and change its direction of motion. Every two-body system in space has five areas of gravitational stability like this, and spacecraft can use these points to easily manoeuvre to different destinations without expending much fuel or energy. Here, we've taken a look at some of the key features of this 'freeway' through the Solar System.



Pluto
NASA's New Horizons probe, currently on its way to Pluto, has made use of gravitational assists on its mission to become the first spacecraft to visit the distant dwarf planet in 2015.

Jupiter
Spacecraft making the journey to Jupiter can make use of gravitational assists around Earth to reach the gas giant, like NASA's Juno spacecraft has done.

Venus
Many spacecraft use Venus for a gravitational assist to the outer Solar System, as the journey towards the planet and the Sun speeds up the probe before using the planet to slingshot back out again.


Space road
This gravity-driven route is a tried and tested way around the Solar System.
Neptune
Reaching Neptune by conventional means would require large amounts of fuel, so future spacecraft could use the superhighway to reach the planet more easily, albeit at the expense of mission duration.
Uranus
Only one spacecraft has ever visited Uranus, Voyager 2, which made use of a rare alignment of the planets to reach the gas giant without using large amounts of fuel.
Saturn
Far into the future, missions mining Saturn's moons could send materials back to outposts at Earth or Mars using the superhighway at relatively little cost.
Mars
Using the interplanetary superhighway for a journey to Mars would take several years, which although long is ideal for unmanned spacecraft looking to use minimal fuel.
Lagrange points
The superhighway works by spacecraft making use of Lagrange points, where the gravity of two bodies cancels each other out, to make turns and alter their direction.
Earth
To travel deep into the Solar System, spacecraft can use Earth as a gravitational slingshot after visiting Venus to reach the outer planets.

Explore the Milky Way

The Spitzer Space Telescope takes a panoramic image through the plane of our galaxy

In five years' time the European Space Agency team behind Gaia will be able compile enough data, from the billion stars surveyed, to determine all their distances and motions. From this they will then be able to create a three-dimensional map of the Milky Way. While not wanting to detract from a clearly incredible achievement, five years is a long time to wait – especially when there's a surveyor already in orbit that has achieved a similar feat in two dimensions, to what Gaia aims to achieve in three.

The Spitzer Space Telescope was launched in 2003 with the primary mission of observing the universe in infrared. It used liquid-helium cryogenic coolant to keep its instruments at a temperature a fraction above absolute zero (-273.15 Celsius or -459.67 Fahrenheit), which was necessary for the telescope to pick out some of the coolest celestial objects in the universe. The coolant ran dry in May 2009, meaning these instruments no longer worked and Spitzer began running at -240 Celsius (-400 Fahrenheit).

Some years prior to the Warm Mission, Spitzer began taking what would amount to over two million infrared images through the plane of the Milky Way. This would be dubbed the GLIMPSE (Galactic Legacy Infrared Mid-Plane Survey Extraordinaire) project. These were combined with data from other surveys and stitched together to create an impressive panorama of the Milky Way.

An infrared view of our galaxy is desirable because light in the visible portion of the electromagnetic spectrum is eventually blocked by dust at an average of about 1,000 light years away, giving us a view of a measly five per cent of the galaxy. Infrared light passes easily through this dust to give us almost a complete view of the Milky Way and its many stars.

From our position, 26,000 light years from the galactic core, GLIMPSE shows us the shape of the galaxy and the position of its spiral arms. The brightest and most vivid section of the panorama marks the centre of the Milky Way, Sagittarius A, a concentrated source of radiation and the thickest point through the galactic plane that Spitzer took its images from. Conversely, the darkest sections are our galactic backwater, where the telescope is looking directly out to the furthest fringes of the galaxy. Here, much fainter and lower-mass stars have been detected that haven't been picked up before. The GLIMPSE project has shown that the Milky Way is slightly bigger than thought and is pocked with bubble-like cavities created by massive stars with powerful stellar winds.

Spitzer's three instruments cover the infrared portion of the spectrum from 160 micrometres to the shortest wavelength sensitivity of 3.6 micrometres. This includes the Infrared Array Camera (IRAC), which has been snapping away with its four modules operating at different wavelengths to help create this iridescent panorama.

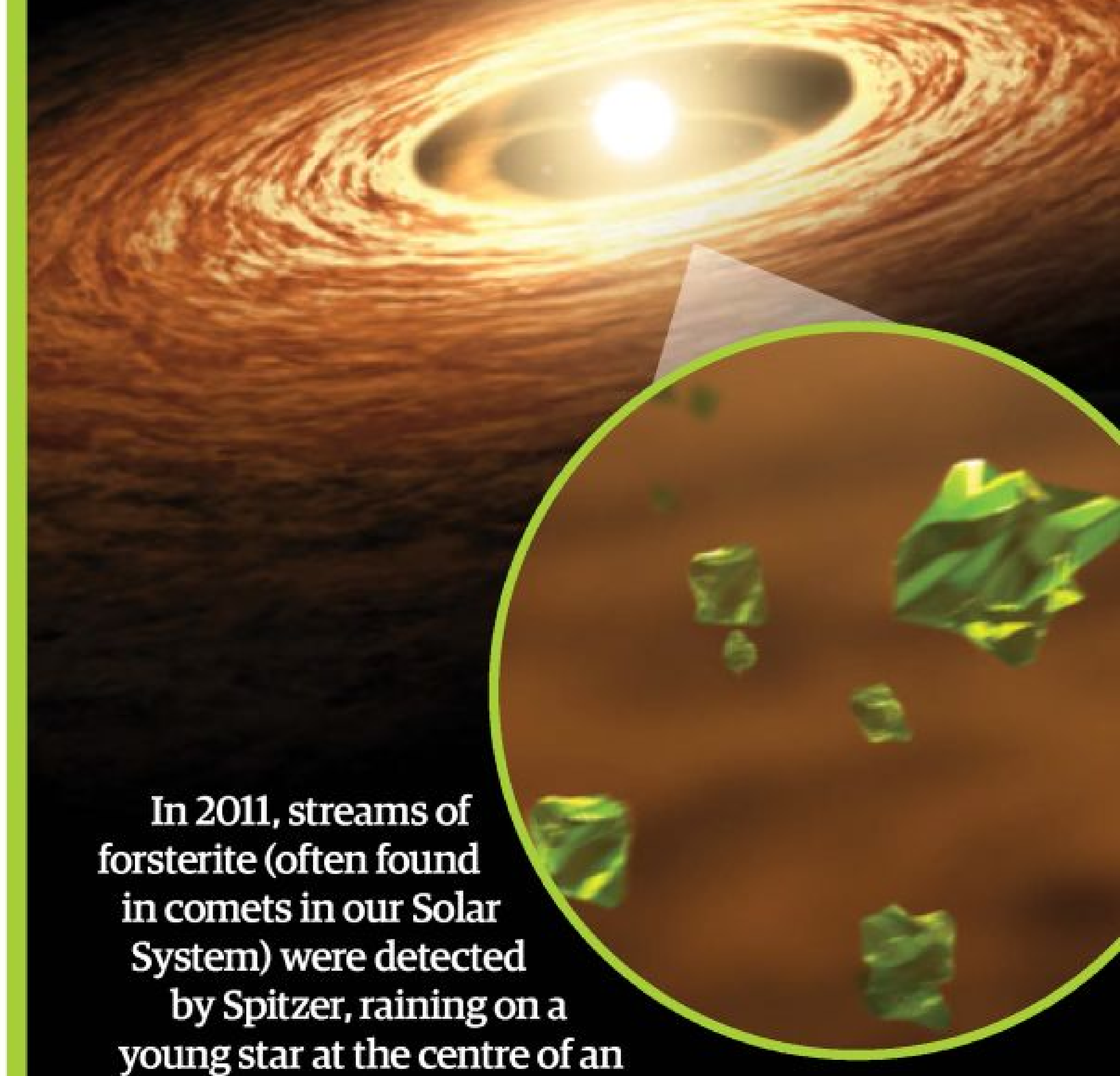
The different colours in the panorama are the various wavelengths of infrared light picked up by IRAC's cameras and MIPS (Multiband Imaging Photometer for Spitzer) imager, at 3.6, 4.5, and 24 micrometres. The coolest regions captured by Spitzer are actually red and were picked up by the camera operating at the longer wavelength of 24 micrometres, marking cloud regions of warm interstellar dust. At a higher wavelength, organic compounds called polycyclic aromatic hydrocarbons are excited by radiation from massive stars and show up in green. Blue and white are the hottest regions, usually thermal emissions direct from mature stars.

The masses of data, in addition to this GLIMPSE panorama, is still being pored over by scientists and will continue to be for years. The data from the image has proven a reliable way to verify astronomical findings and discover new objects.

Read on to see the full panorama of the Milky Way, as pictured by the Spitzer Space Telescope

> "Spitzer began taking what would amount to over two million infrared images"

What has the GLIMPSE survey found?



In 2011, streams of forsterite (often found in comets in our Solar System) were detected by Spitzer, raining on a young star at the centre of an early-stage planetary system

Apart from giving us a better idea of the shape and size of the Milky Way, scientists have discovered masses of new celestial features by scrutinising the data from Spitzer's GLIMPSE survey. This includes over 20,000 red sources, three quarters of which are stars in the making and a quarter of which are evolved stars. Over 500 variable stars have been discovered, 591 polycyclic aromatic hydrocarbon bubbles created by the stellar wind from massive stars and 59 new star clusters spotted. Spitzer's primary mission came to an end five years ago when its coolant ran out, but these figures are changing all the time as more data is processed.

GLIMPSE by numbers

2 gigapixels went into creating the full-size image.

46 sq m *is the area the full image would cover.*

100,000x size difference between the smallest and largest objects.

50% of the galaxy is captured in the panorama.

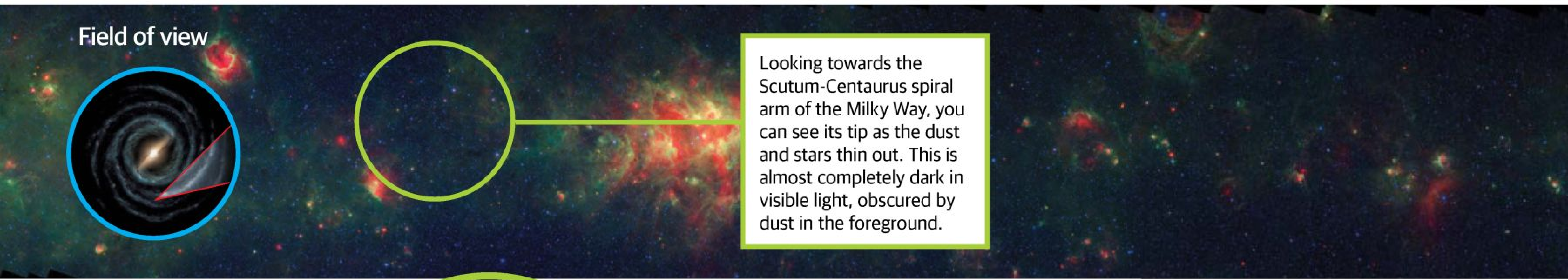
2 million infrared images created this result.

800,000 individual frames were stitched together to create the panorama.

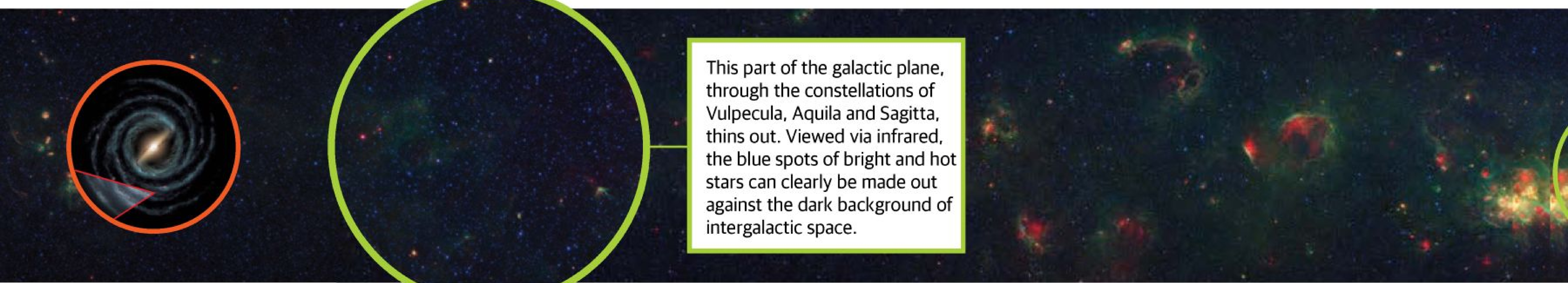
95% of the galaxy is hidden in visible light.

100 million *stars catalogued as a result of the survey.*

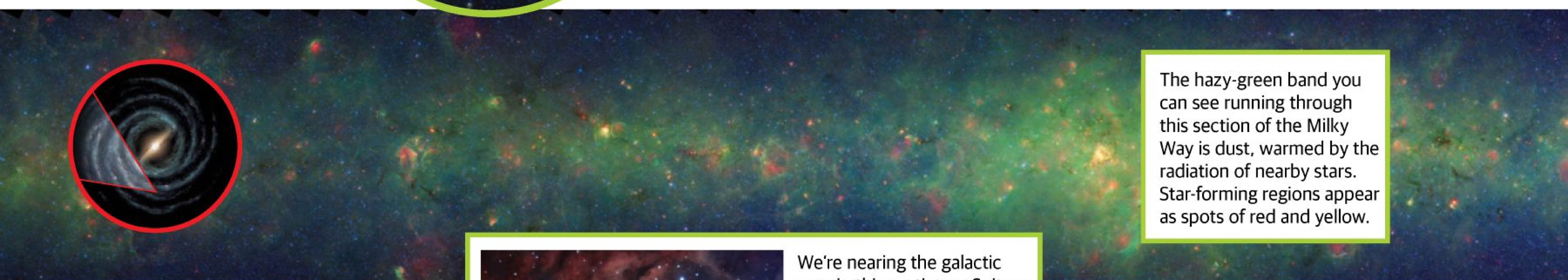
150 billion stars are captured in this image.



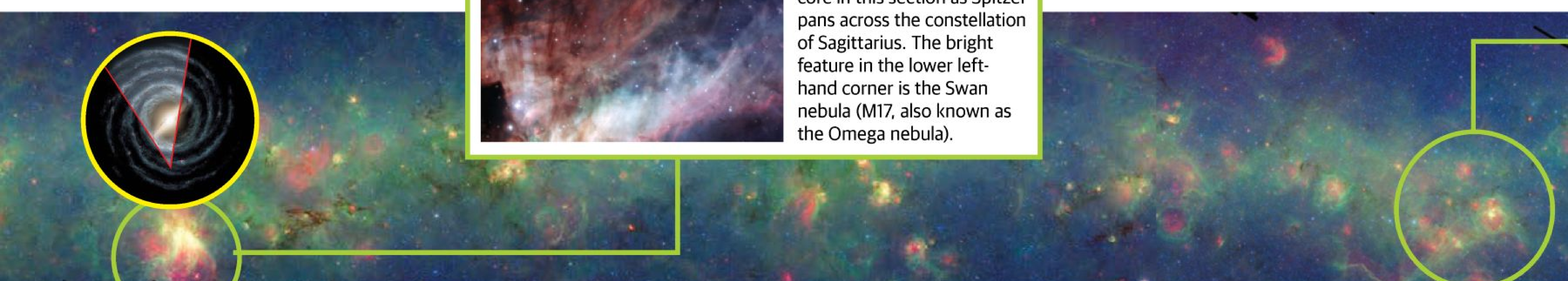
Looking towards the Scutum-Centaurus spiral arm of the Milky Way, you can see its tip as the dust and stars thin out. This is almost completely dark in visible light, obscured by dust in the foreground.



This part of the galactic plane, through the constellations of Vulpecula, Aquila and Sagitta, thins out. Viewed via infrared, the blue spots of bright and hot stars can clearly be made out against the dark background of intergalactic space.

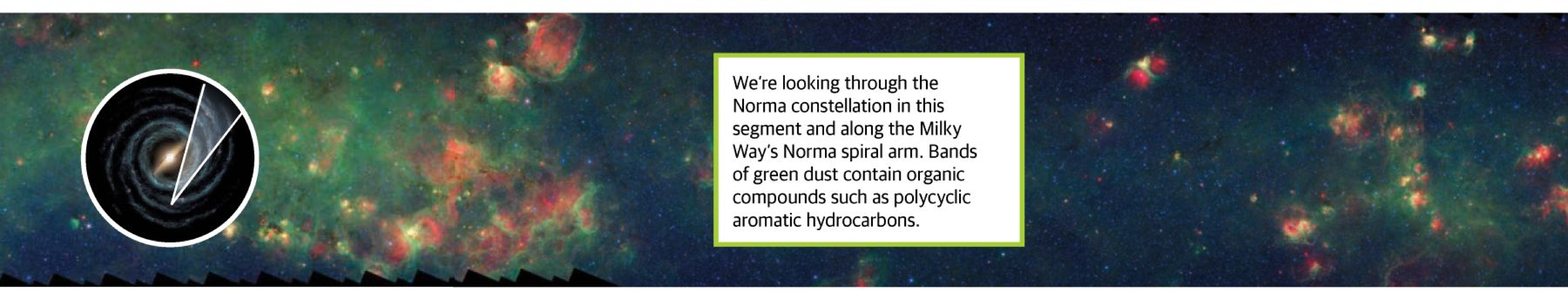


The hazy-green band you can see running through this section of the Milky Way is dust, warmed by the radiation of nearby stars. Star-forming regions appear as spots of red and yellow.

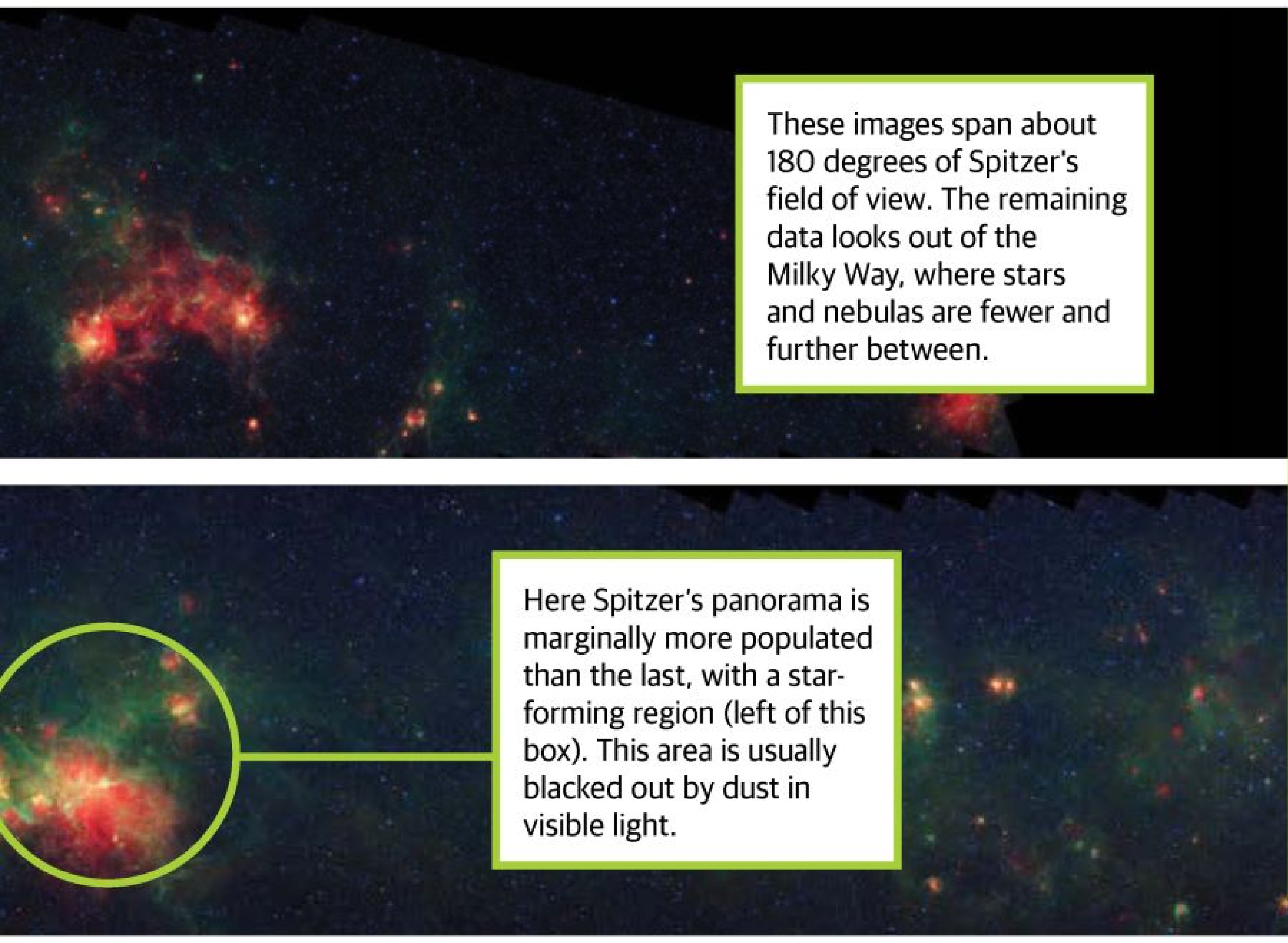


We're nearing the galactic core in this section as Spitzer pans across the constellation of Sagittarius. The bright feature in the lower left-hand corner is the Swan nebula (M17, also known as the Omega nebula).

As Spitzer pans away from the centre of the galaxy, it crosses NGC 6334 – otherwise known as the Cat's Paw nebula. This nebula can also be seen in visible light.



We're looking through the Norma constellation in this segment and along the Milky Way's Norma spiral arm. Bands of green dust contain organic compounds such as polycyclic aromatic hydrocarbons.

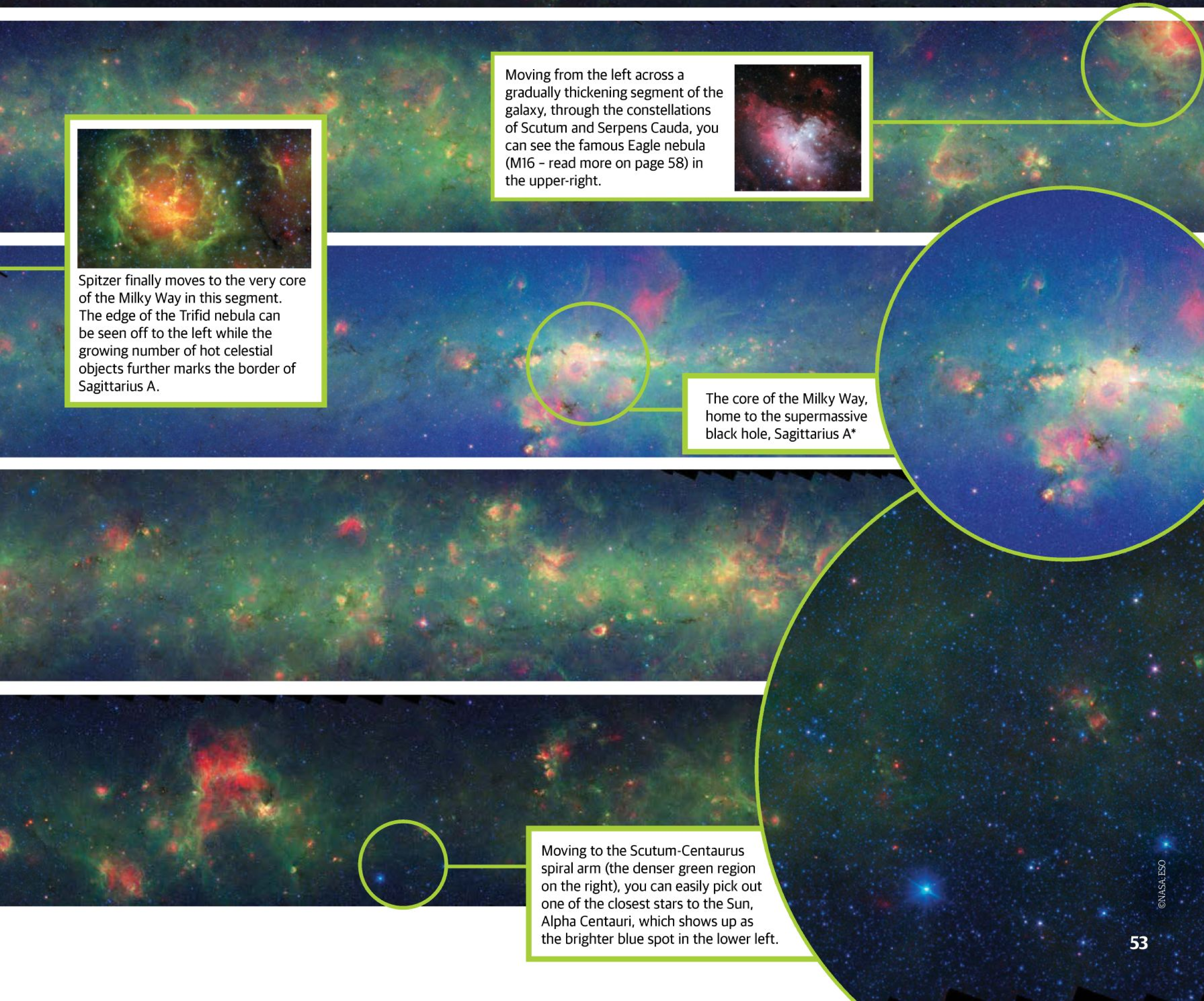


These images span about 180 degrees of Spitzer's field of view. The remaining data looks out of the Milky Way, where stars and nebulas are fewer and further between.

Here Spitzer's panorama is marginally more populated than the last, with a star-forming region (left of this box). This area is usually blacked out by dust in visible light.

What am I looking at?

The Solar System occupies a tiny space about two thirds of the way out from the galactic core to the edge of the galaxy, while the shape of the Milky Way is a flat spiral with a bulbous centre. From its vantage point, around 150 million kilometres (93 million miles) away, the Spitzer Space Telescope can see through the plane of the galaxy. By taking infrared images, the full galaxy is shown to be a long, flat panorama that doesn't show the the spiral arms, but does show the texture and depth of the Milky Way.



Moving from the left across a gradually thickening segment of the galaxy, through the constellations of Scutum and Serpens Cauda, you can see the famous Eagle nebula (M16 – read more on page 58) in the upper-right.

Spitzer finally moves to the very core of the Milky Way in this segment. The edge of the Trifid nebula can be seen off to the left while the growing number of hot celestial objects further marks the border of Sagittarius A.

The core of the Milky Way, home to the supermassive black hole, Sagittarius A*

Moving to the Scutum-Centaurus spiral arm (the denser green region on the right), you can easily pick out one of the closest stars to the Sun, Alpha Centauri, which shows up as the brighter blue spot in the lower left.

Solar System

From the Kármán line to beyond the orbit of Pluto

"It had been captured by the merciless and monstrous gravitational pull of Jupiter"

72
Impact on Jupiter

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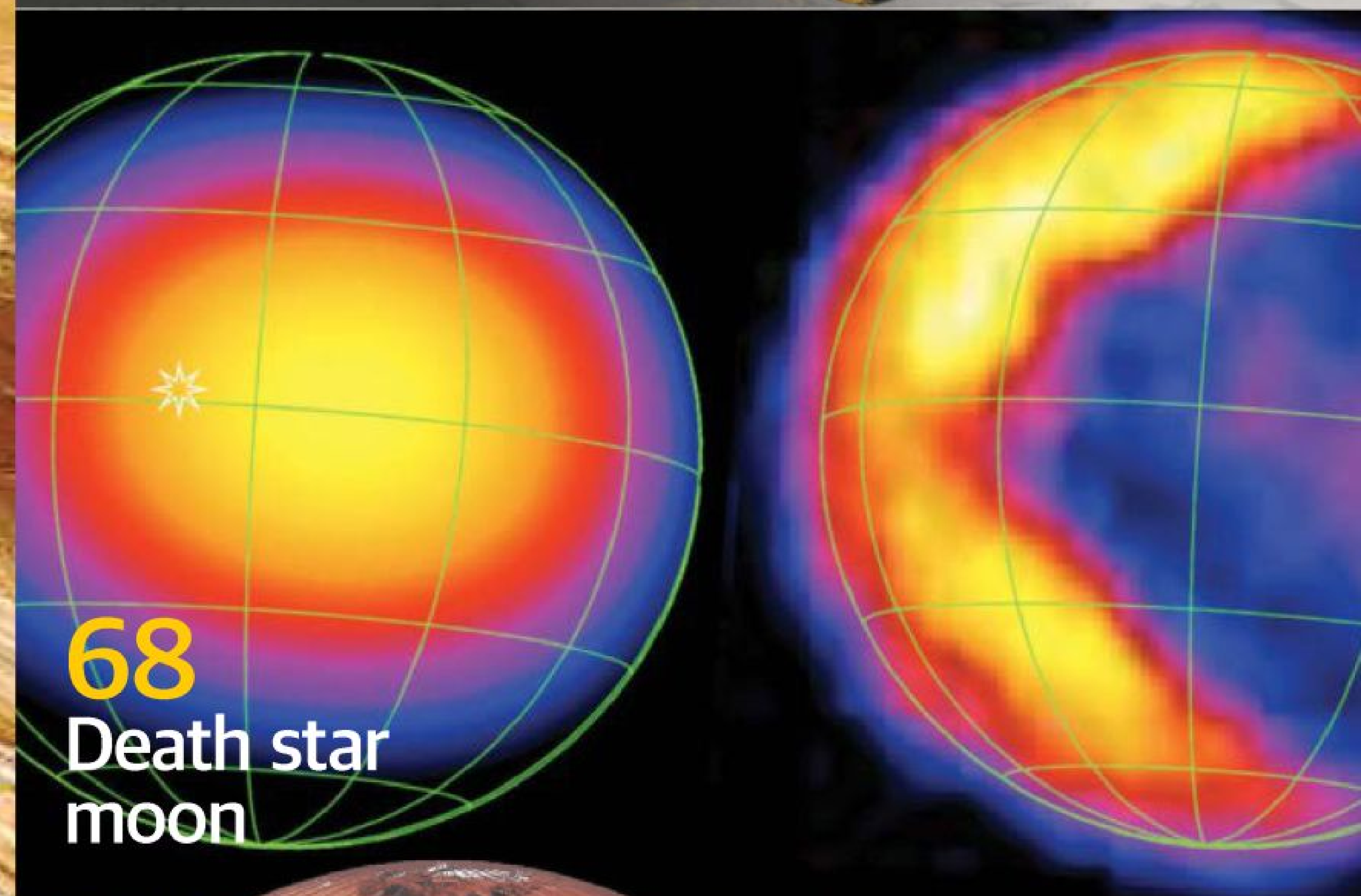
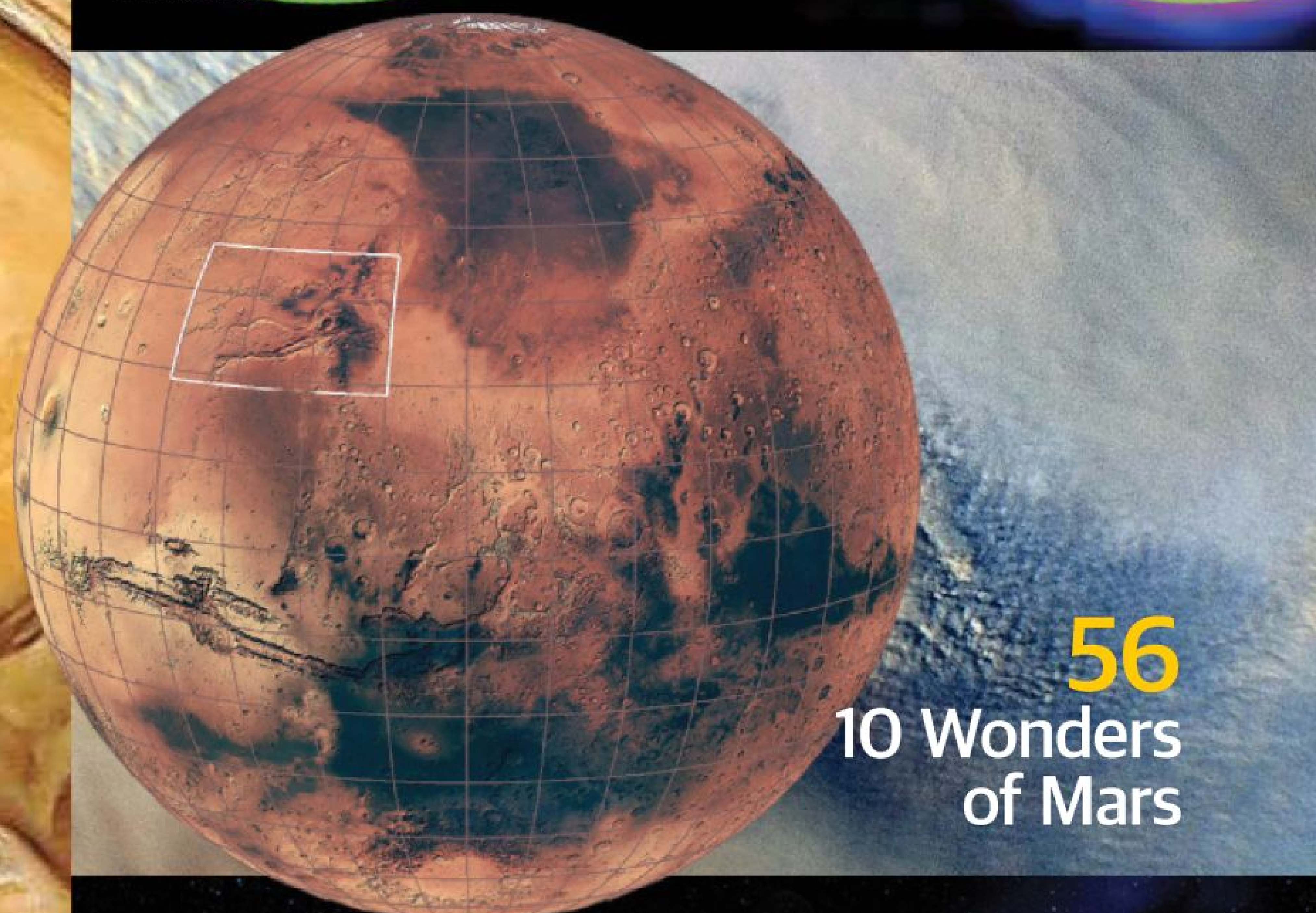
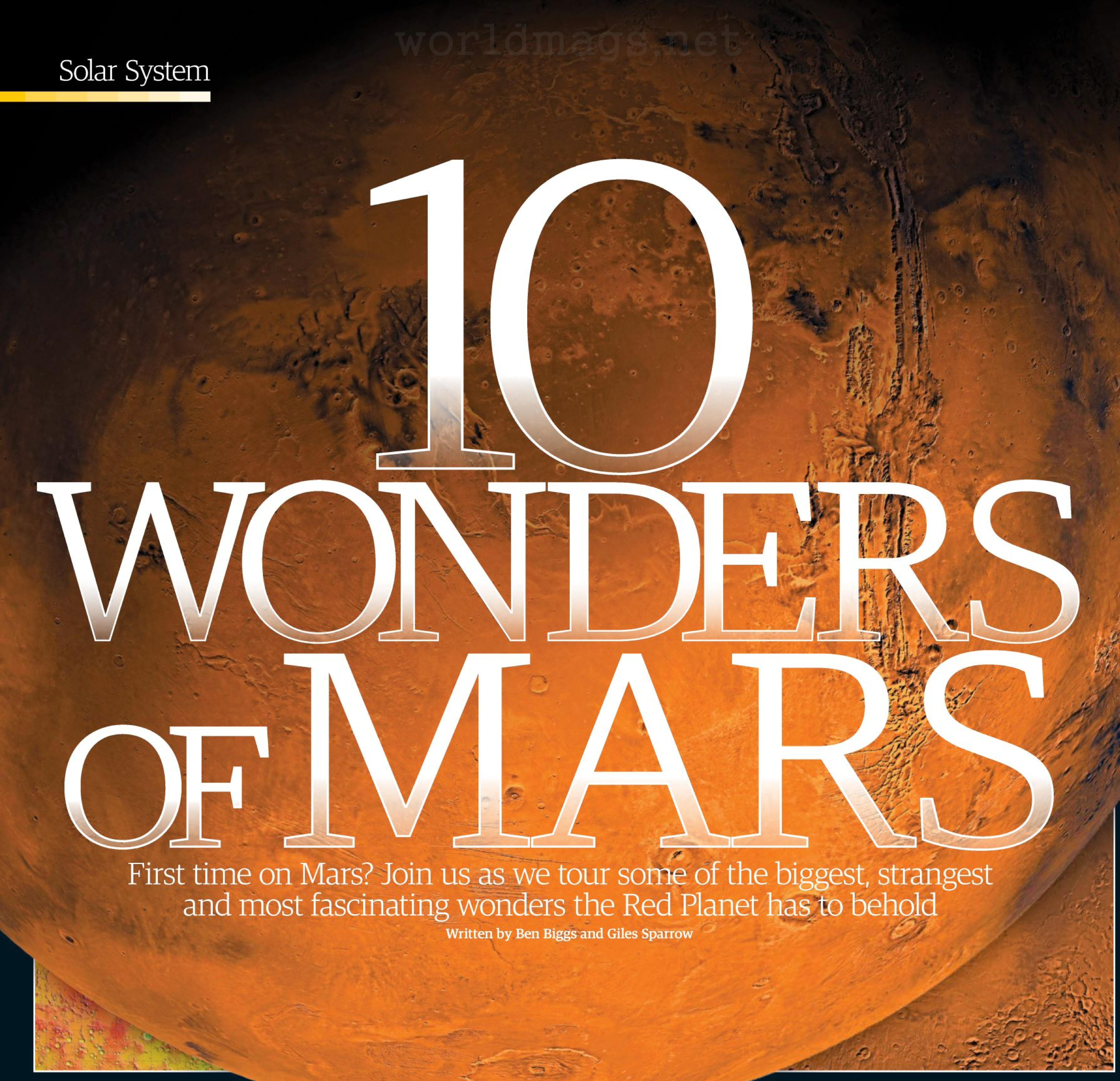


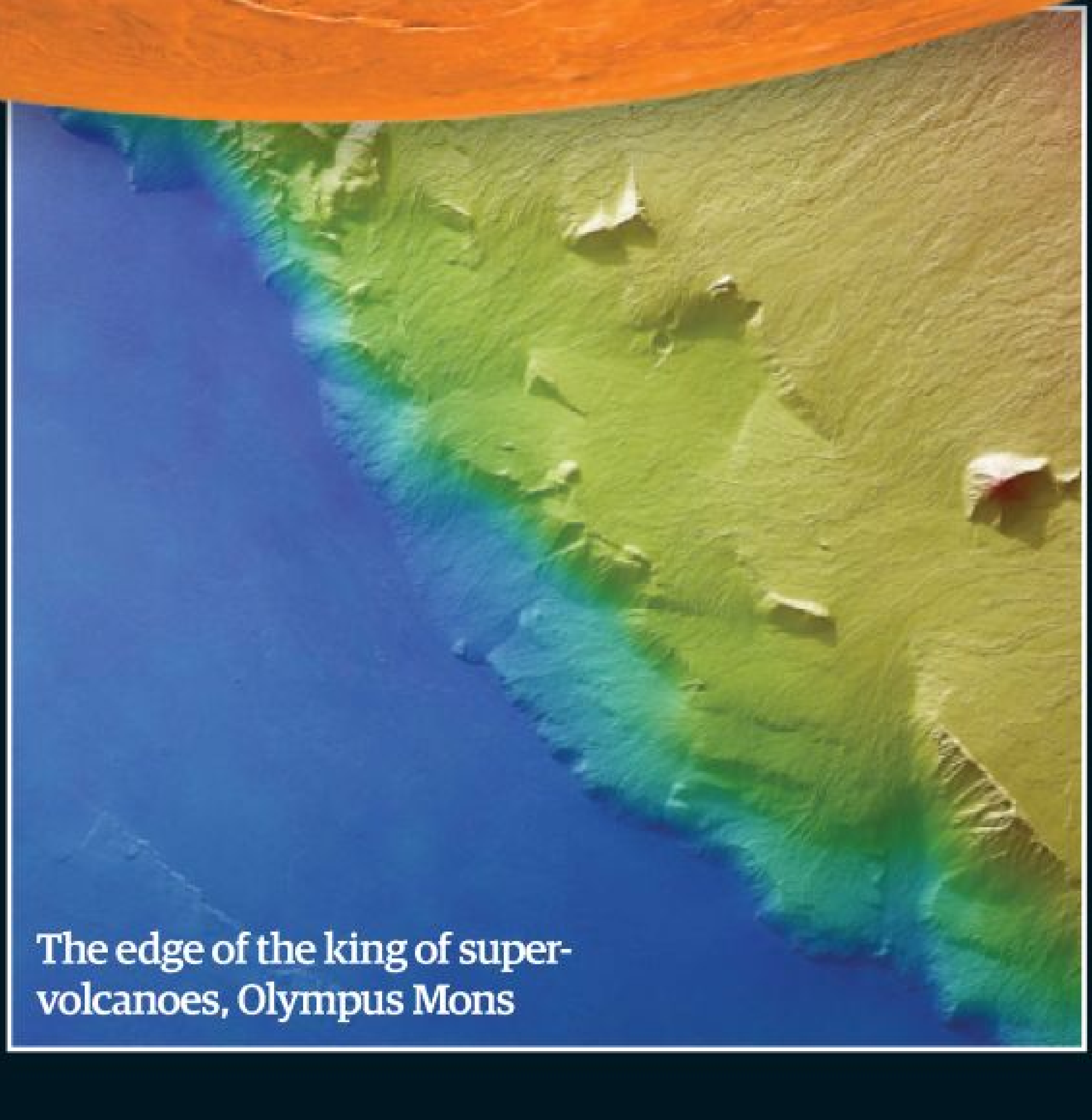




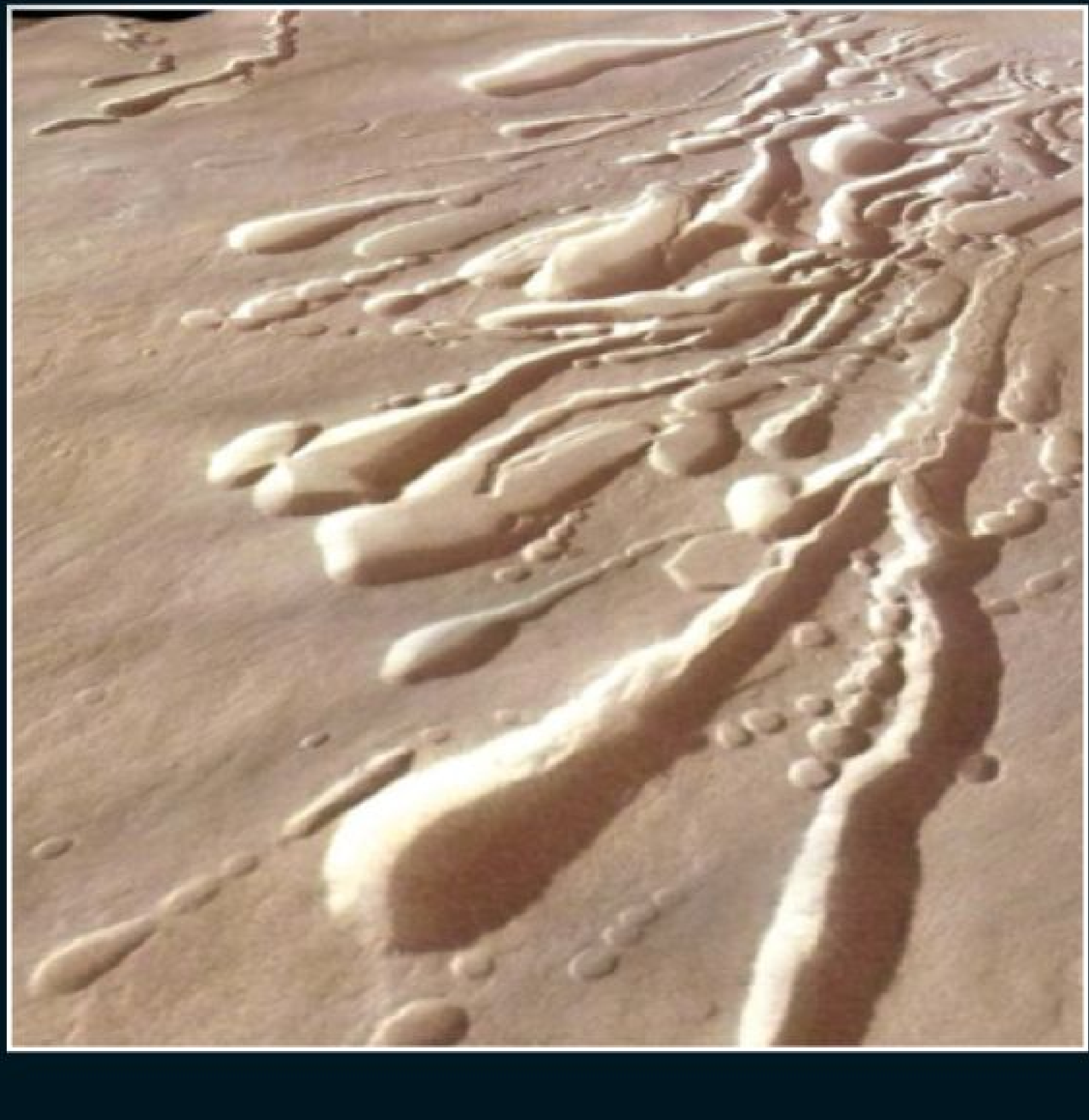
10 WONDERS OF MARS

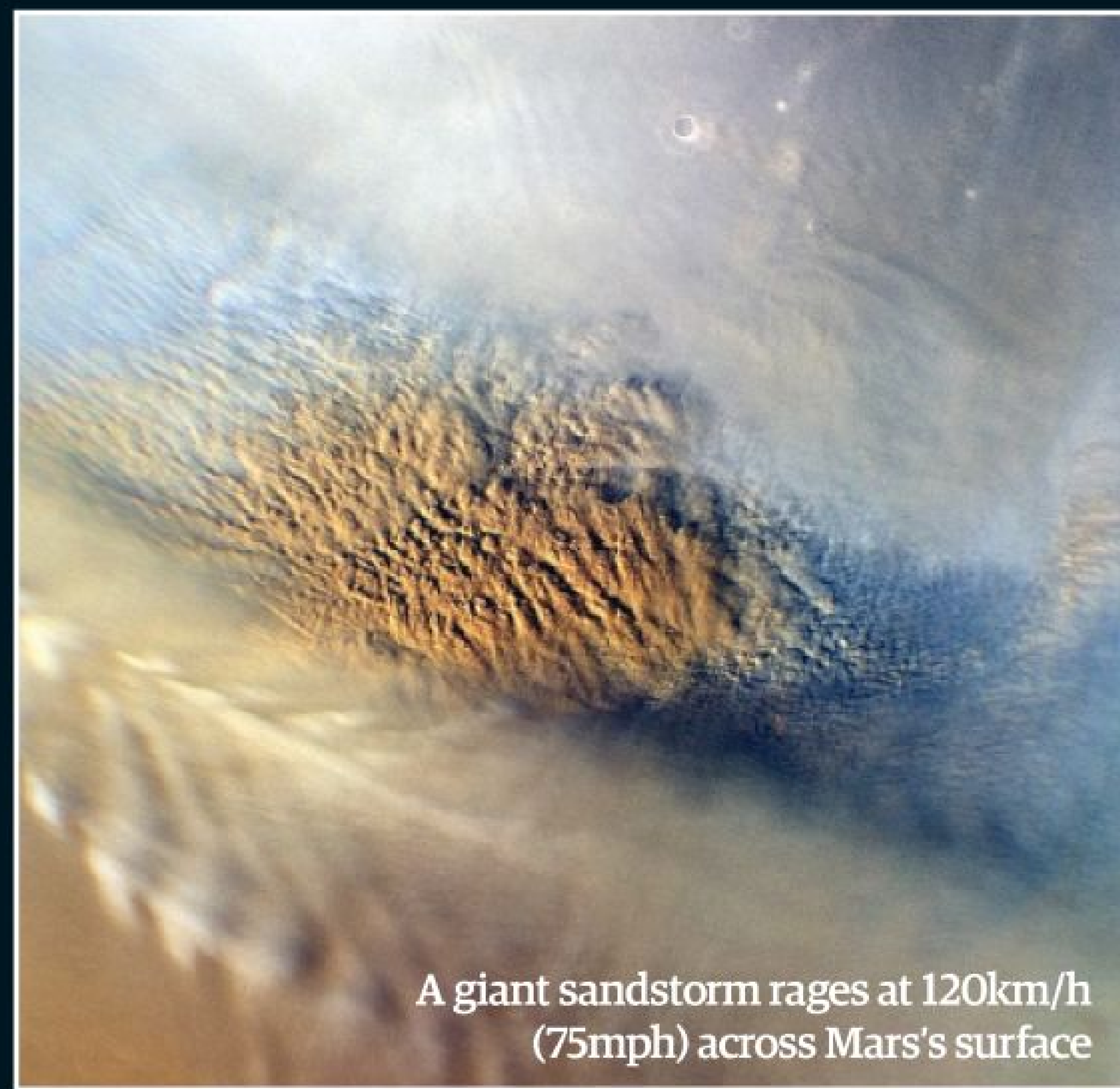
First time on Mars? Join us as we tour some of the biggest, strangest and most fascinating wonders the Red Planet has to behold

Written by Ben Biggs and Giles Sparrow



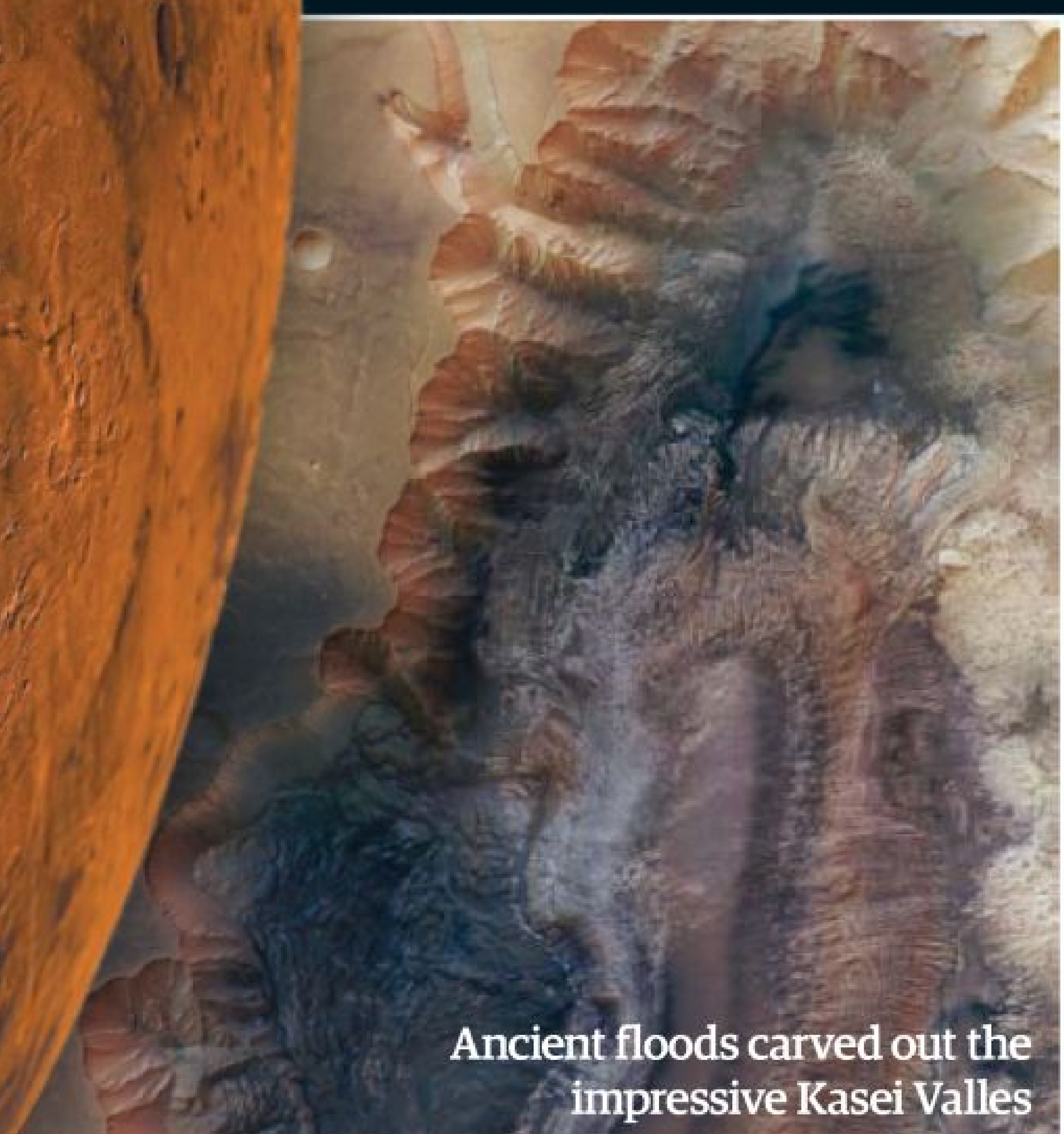
The edge of the king of super-volcanoes, Olympus Mons



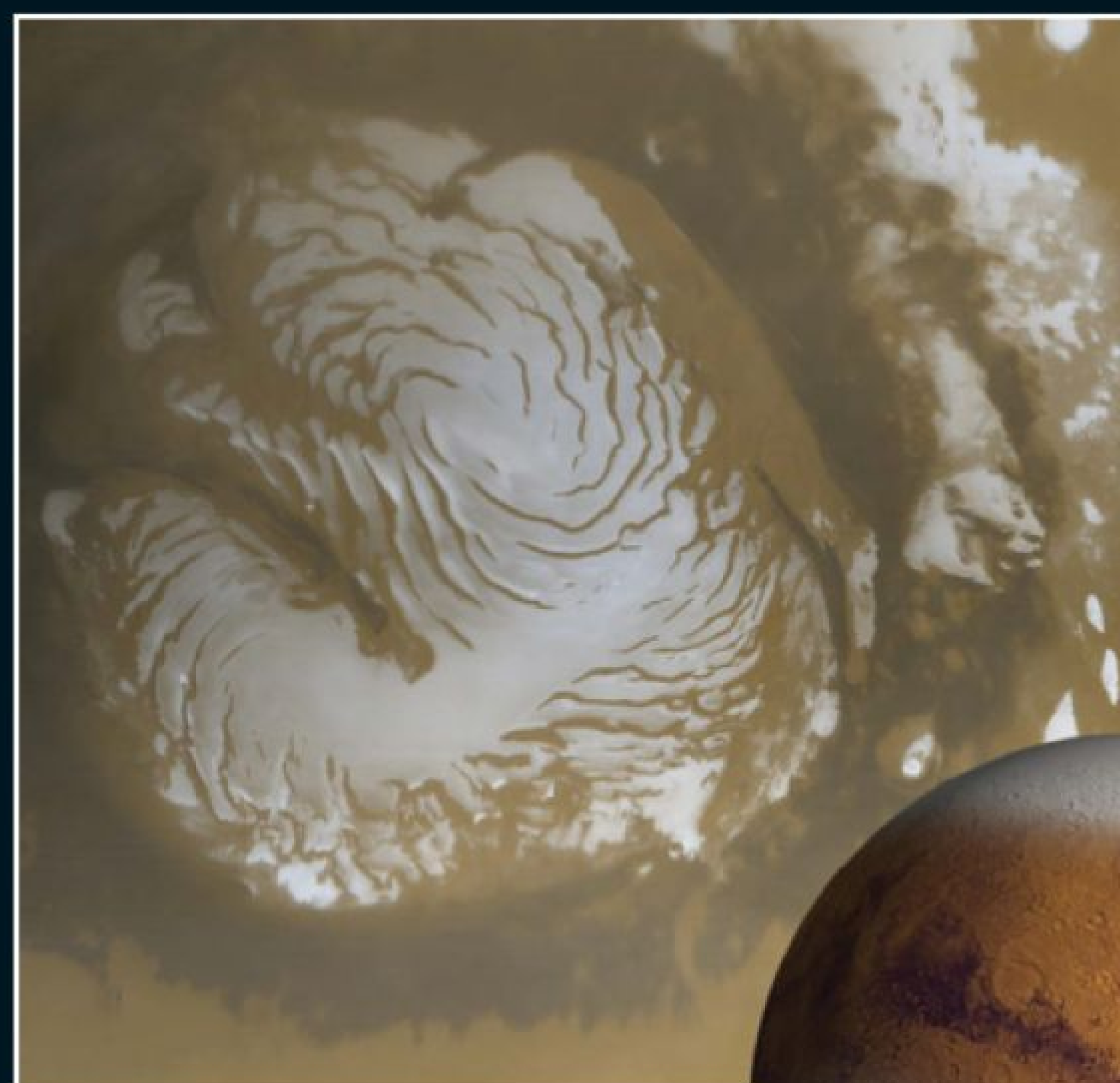


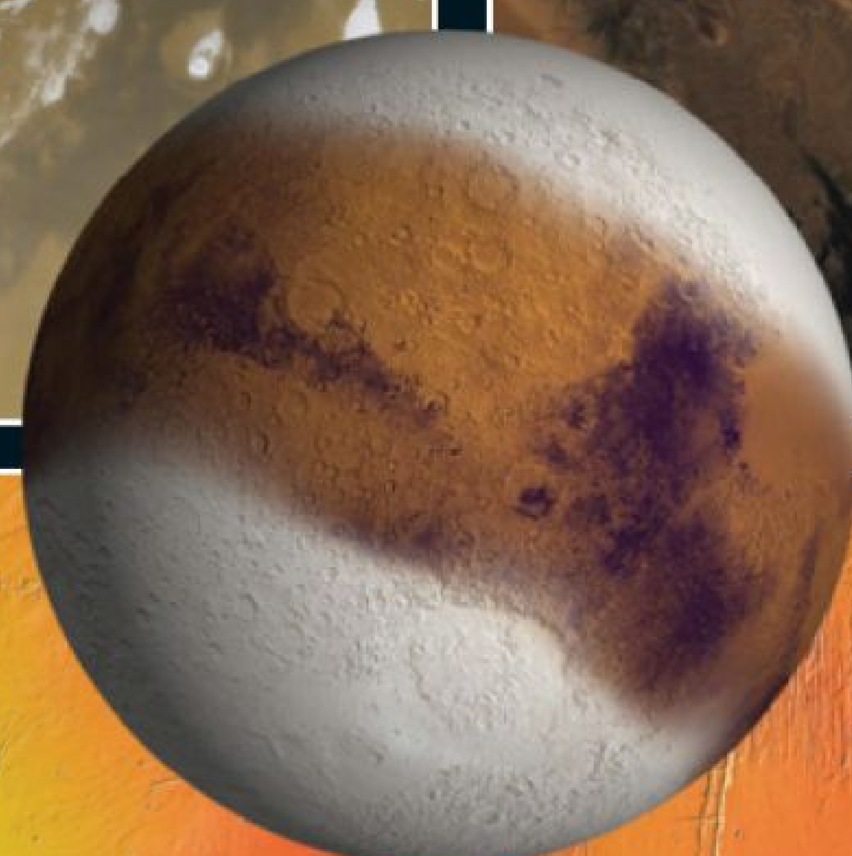
A giant sandstorm rages at 120km/h (75mph) across Mars's surface

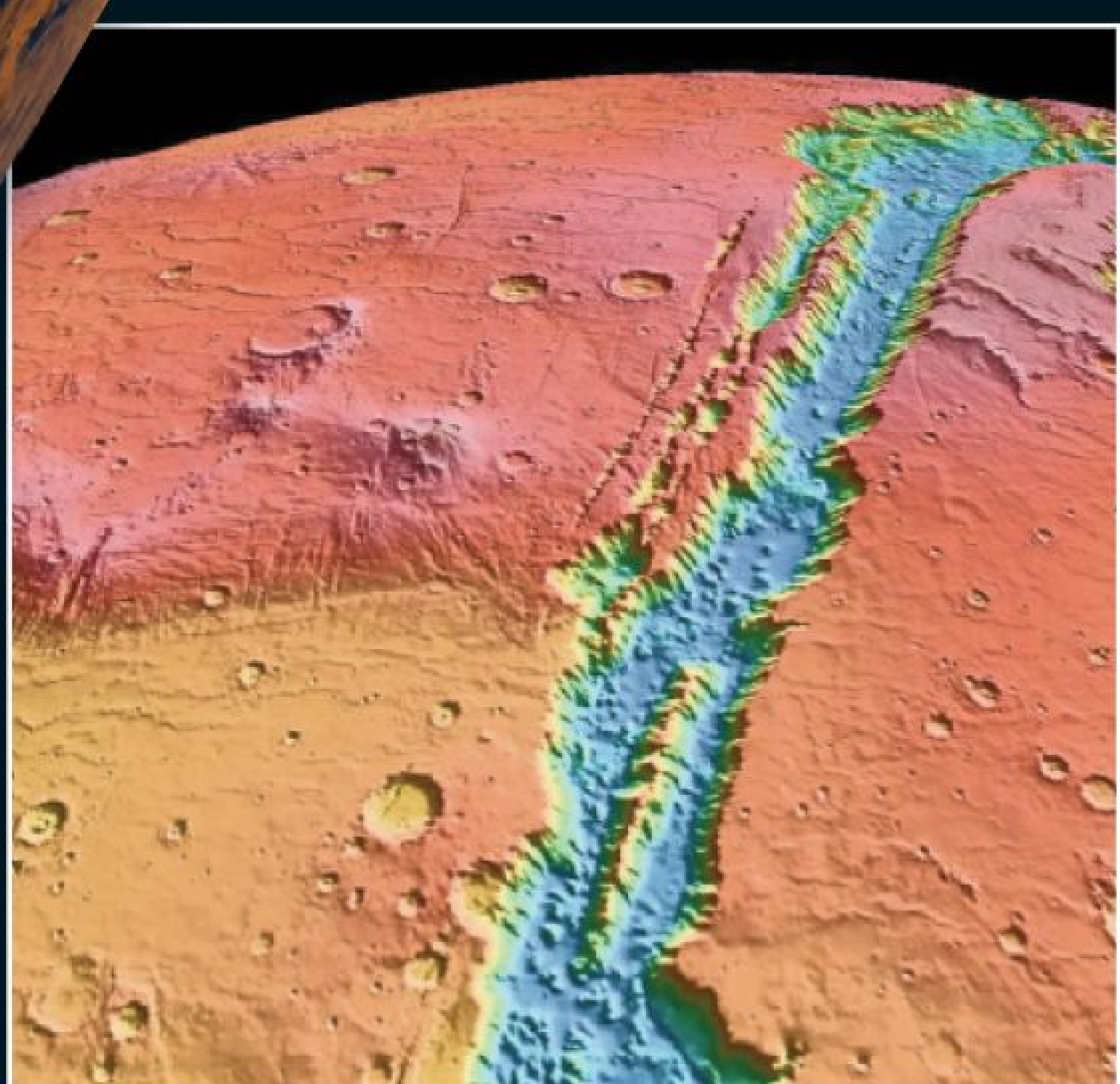
Valles Marineris is over 10km (6mi) deep in places

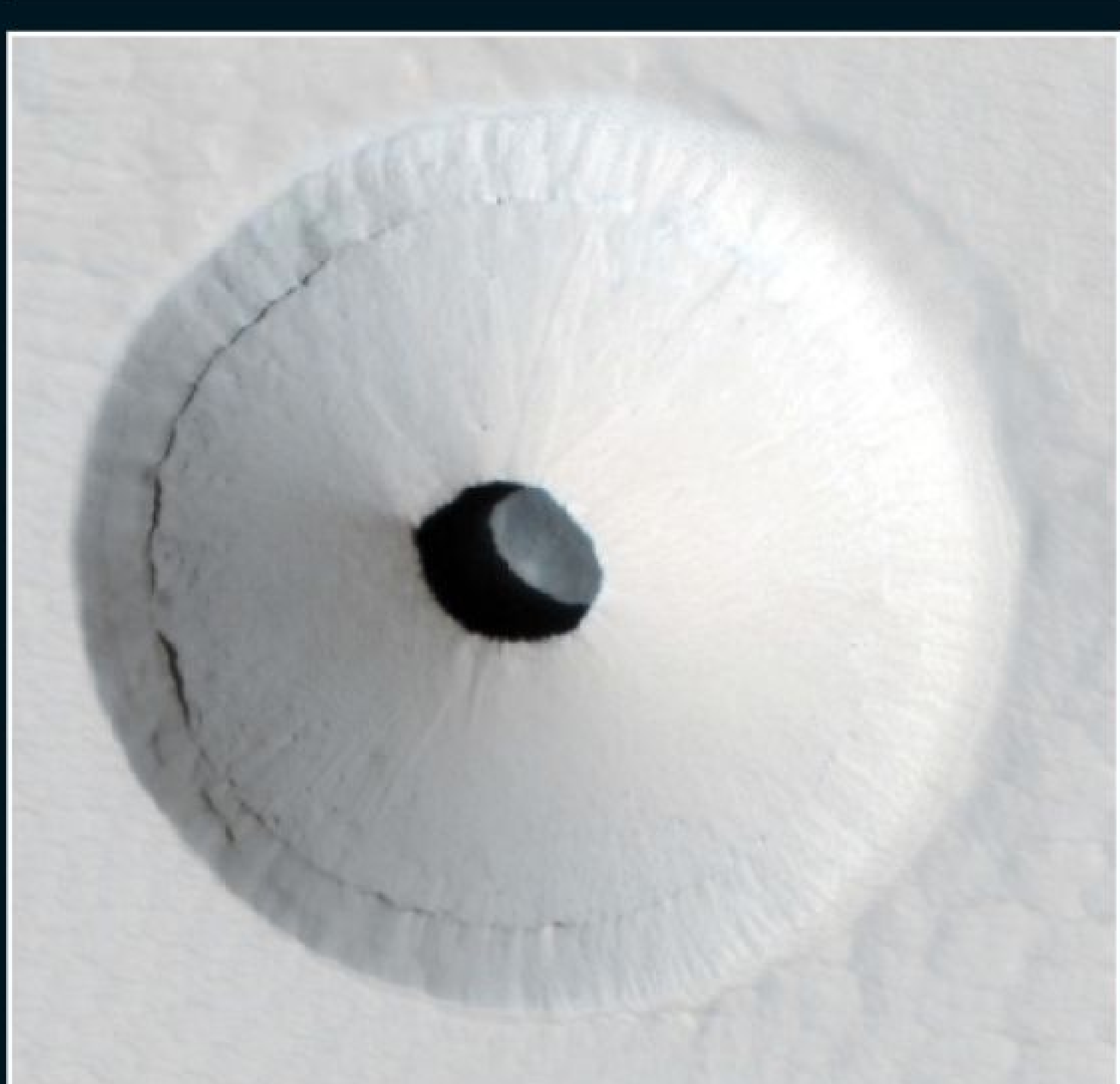


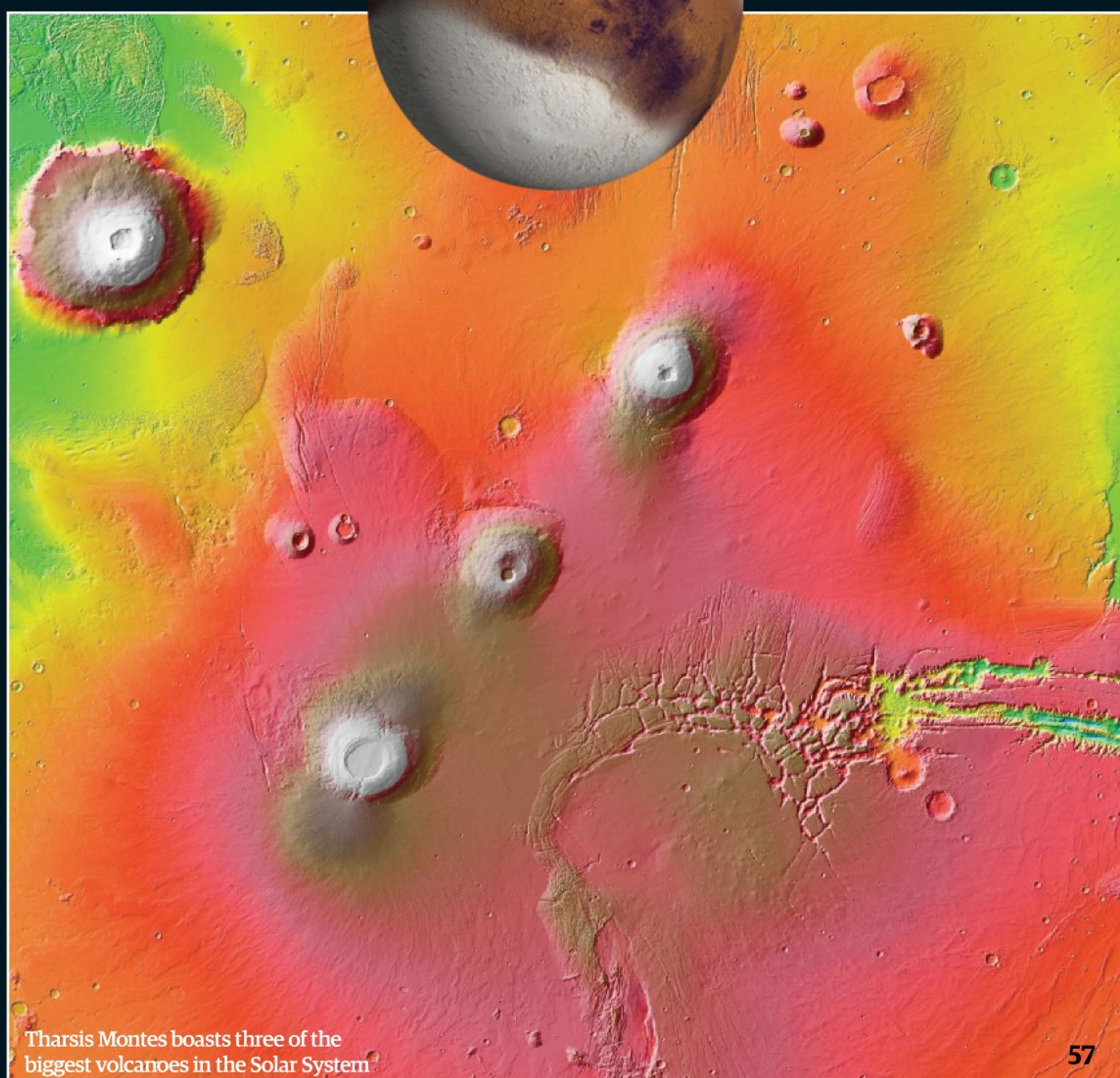
Ancient floods carved out the impressive Kasei Valles



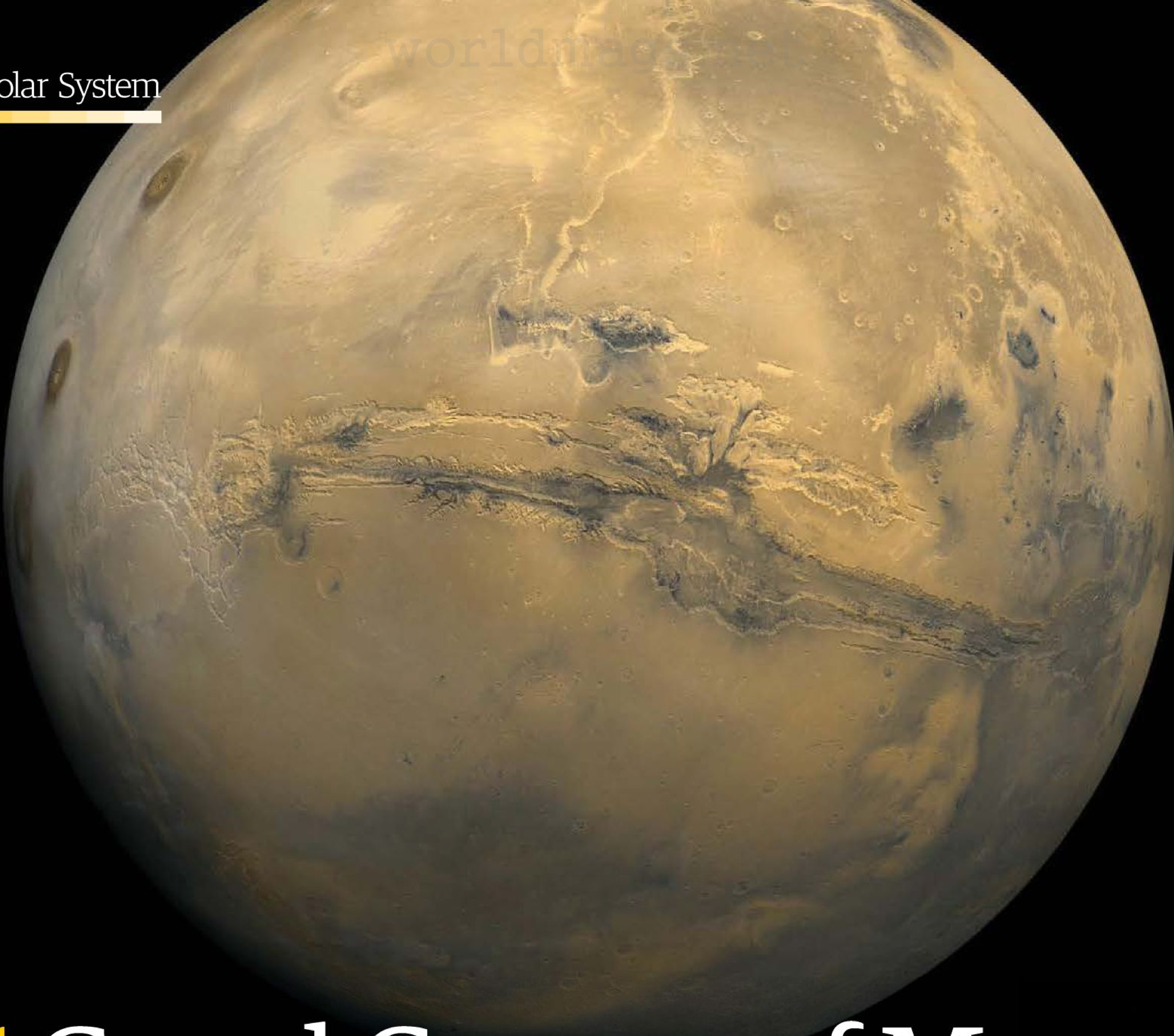








Tharsis Montes boasts three of the biggest volcanoes in the Solar System



1 Grand Canyon of Mars

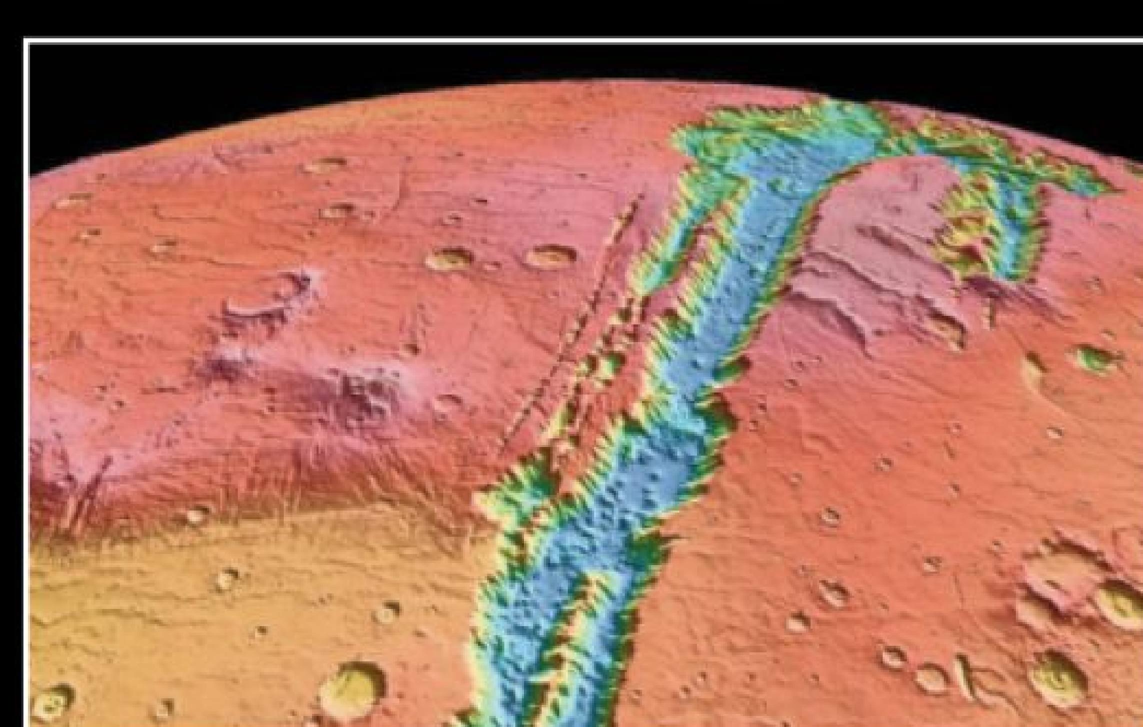
Welcome to Valles Marineris – the biggest canyon in the entire Solar System

It's difficult to recount exactly the impact the Grand Canyon has on you on your first visit. It's pretty overwhelming: at around 29 kilometres (18 miles) at its widest point and nearly two kilometres (1.2 miles) from the plateau to the Colorado River at its deepest, it's probably the biggest thing anyone could hope to witness in their lives. Yet the entire Grand Canyon would be no more than a mere gully in the biggest canyon in the Solar System.

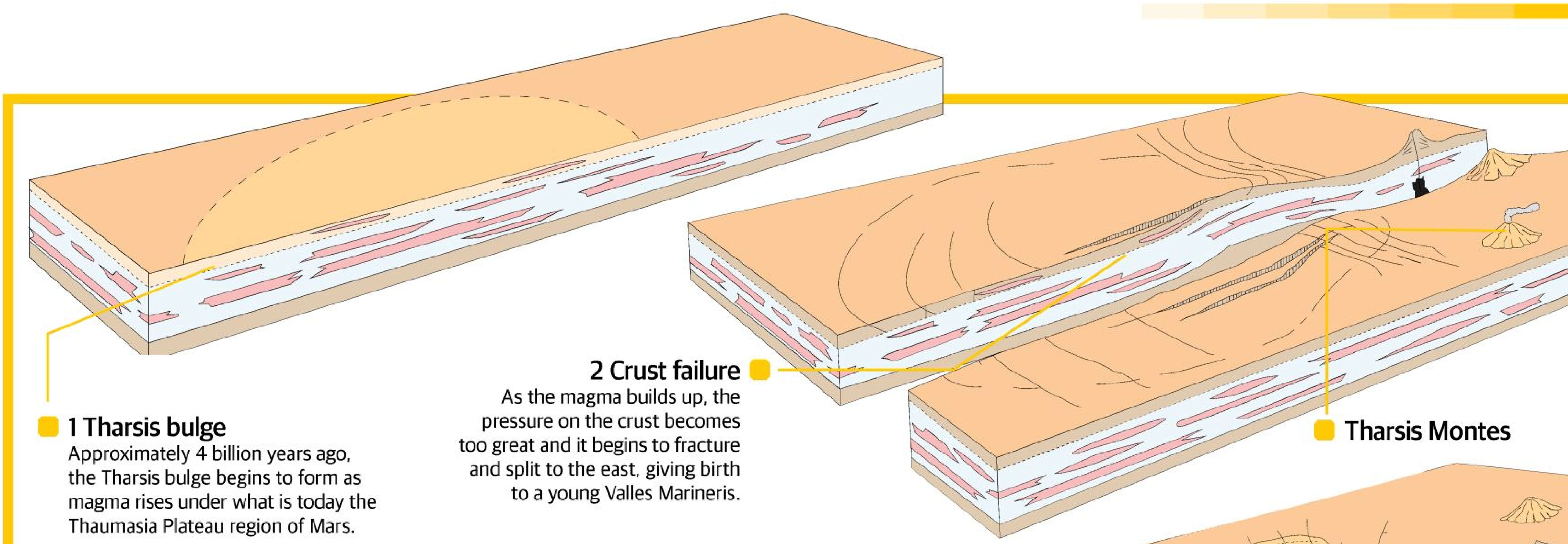
Valles Marineris is unbelievably enormous, spanning over 4,000 kilometres (2,500 miles) in length, with some parts of it 200 kilometres (125 miles) wide and over ten kilometres (six miles) deep. It would stretch across the entire United States if it was on Earth and its size is only exaggerated by the fact that Mars is around half the size of Earth – around 20 per cent of Mars's circumference is taken up by this massive gouge in its surface.

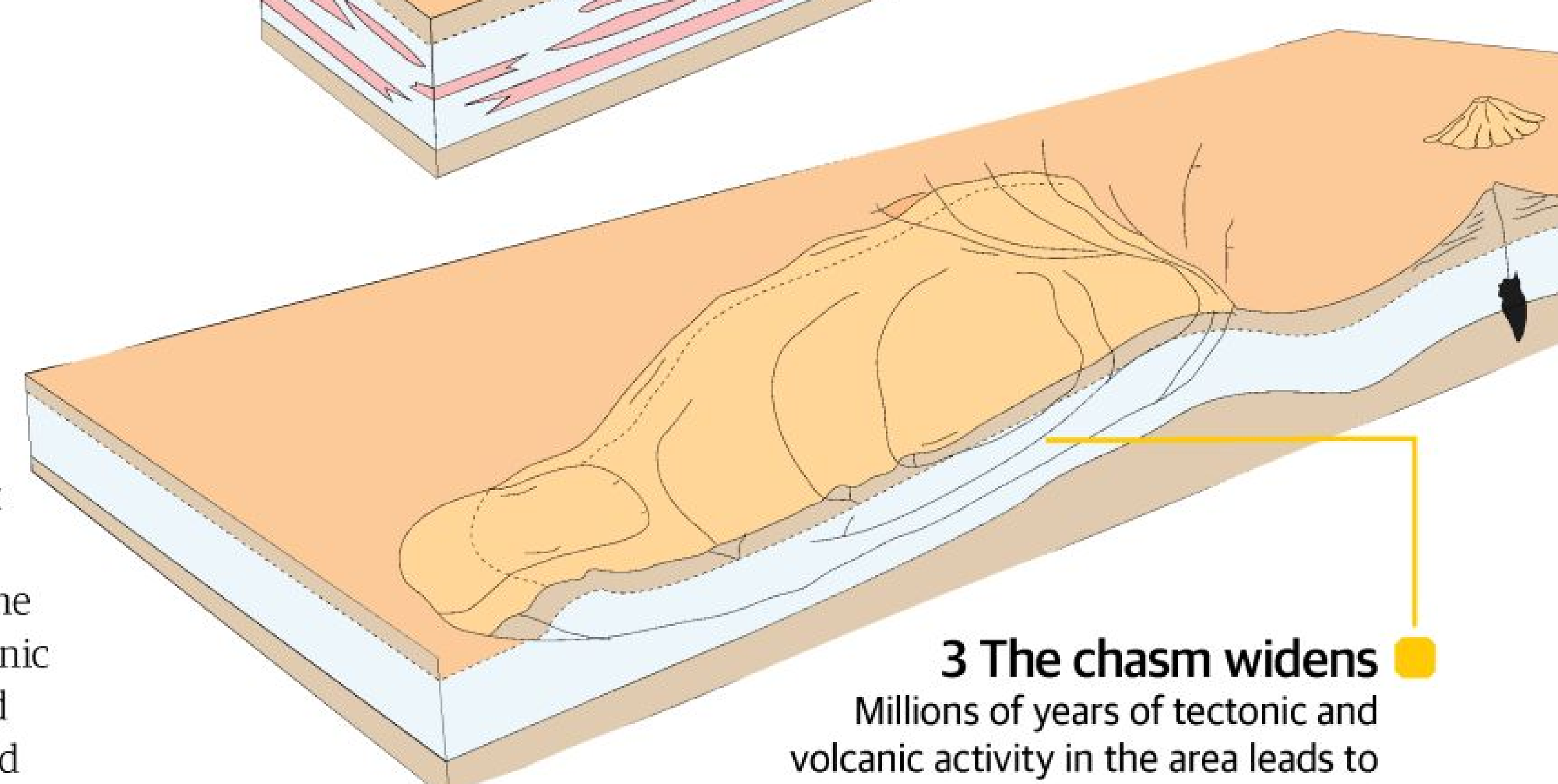
The canyon is, naturally, host to a plethora of interesting geological features that offer scientists clues as to its turbulent past. Located just south of Mars's equator, its western end begins with a series of steep, maze-like valleys given the sinister Latin title Noctis Labyrinthus, or 'the labyrinth of the night'. This region shows typical fault-line activity, with valley-forming depressions known as 'grabens'. Moving eastwards, Valles Marineris starts to grow in breadth and depth, with twin canyons called the Ius and Tithonium chasmata running parallel to each other, divided by a central ridge. This gives way to three more chasmata and the deepest part of the canyon at 11 kilometres (6.8 miles) from the plains above. These eventually lead to the eastern end: Coprates Chasma, defined by its layered deposits that could originate from landslides or water erosion, Eos and the Ganges chasmata and, finally, where the canyon terminates in the Chryse region, a mere kilometre (0.62 miles) above Valles Marineris's deepest point.

Although there's evidence of a number of processes at work here including water erosion, the scientific community generally agrees today that the volcanic region west of Valles Marineris played a major role in the formation of this huge rift, with water reshaping and deepening its course. It's thought that as the Tharsis Montes was pushed up my molten rock to form gigantic volcanoes, the crust split to form fault lines around 3.5 billion years ago, which inevitably widened to form Valles Marineris. Though they share many similarities, this is unlike the Grand Canyon, which was gradually carved out of the surrounding rock millions of years ago by the meandering of the Colorado River and its tributaries.



A topographical map, showing the depth of the canyon

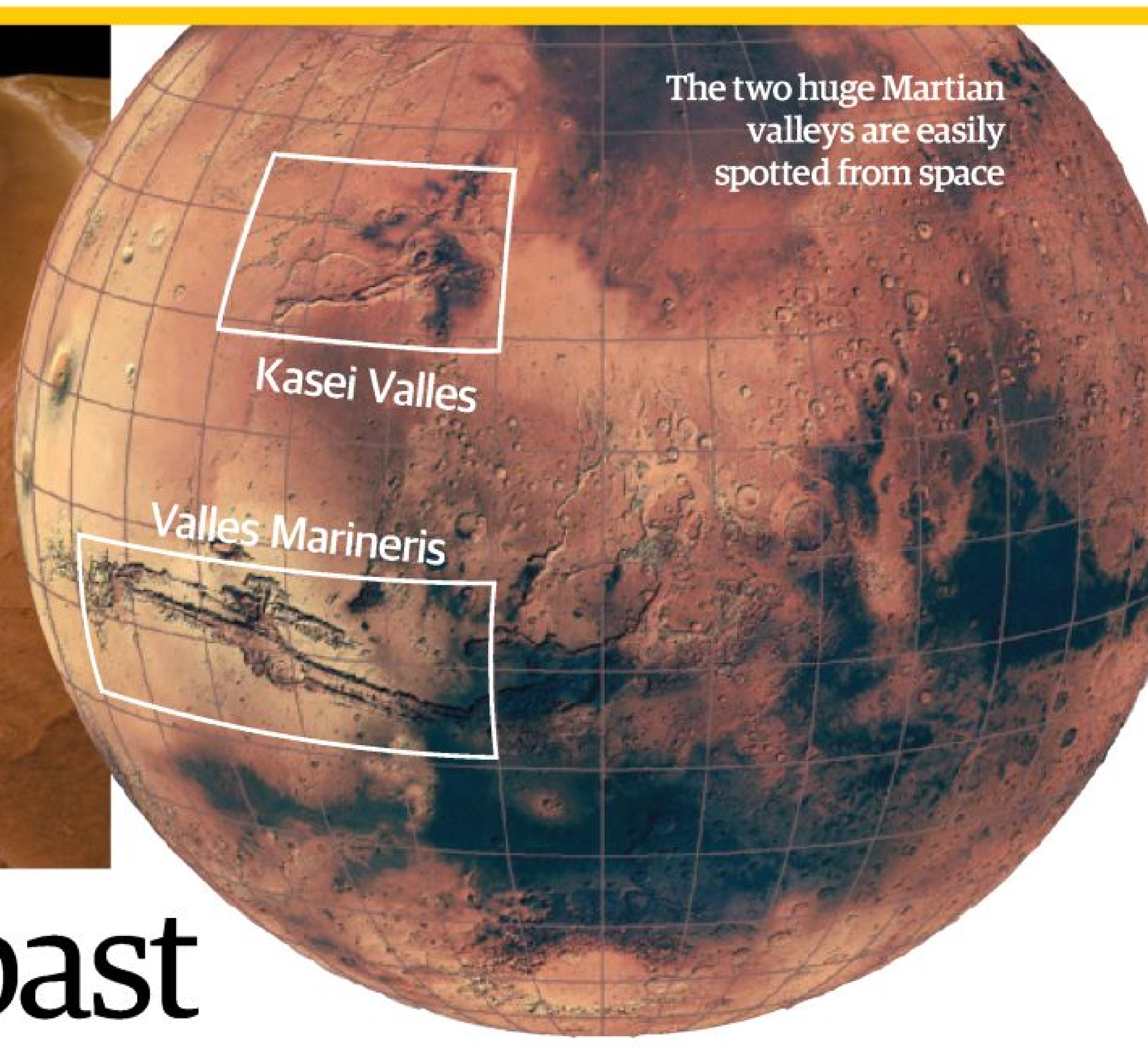




How Valles Marineris formed

It's thought that Valles Marineris is an example of a giant rift valley, similar to Africa's rift valley system. Its formation is primarily tectonic and consists of three main stages that begins with the Tharsis bulge, a region where Valles Marineris is today that began to uplift as magma rose, as early as 4 billion years ago. The pressure and extra weight of magma led to parts of the crust forming graben – valleys sunk along fault lines. The crust then began to float on the magma and, pushed to breaking point, splits along the length of Valles Marineris. Finally, tectonic activity, landslides, asteroid impacts and even meltwater could have widened and deepened the long chasm to form Valles Marineris as we see it today.


This massive canyon was carved out by torrents of water



The two huge Martian valleys are easily spotted from space

2 Chasm with a violent past

Meet Valles Marineris's little brother

If it weren't for its bigger sibling several hundred kilometres to the south, Kasei Valles would have taken the gong for being the biggest canyon system on Mars, if not the Solar System. As it stands, its 3,000-kilometre (1,900-mile) expanse, three-kilometre (1.8-mile) depth is still more than prominent enough to stand out from the surface to any passing orbiter. It even tops Valles Marineris in places, reaching over 300 kilometres (185 miles) wide.

Its size isn't what makes Kasei Valles a wonder of Mars alone though. All 1.5 million square kilometres (nearly 600,000 square miles) of the region were forged by some of the most violent events in Mars's history. Today, the most potent force Kasei Valles faces is the occasional, turbulent dust storm that, given the thin Martian atmosphere, is hardly about to carve another record-breaking canyon into it any time soon. It was a different story over 3 billion years ago, though: the same raging tectonics that were busy creating Valles Marineris were ripping the landscape apart further north, bringing groundwater to the surface which combined with ice melted by the volcanoes further west to create furious torrents of mud, forming and shaping the channels of Kasei Valles. The same violent floods failed to completely erode the outcrop of Sacra Mensa but further downstream, they made mincemeat of the southern rim of the 100-kilometre (62-mile) Sharonov crater, before emptying into the plain of Chryse Planitia.

> "The region was forged by some of the most violent events in Mars's history"

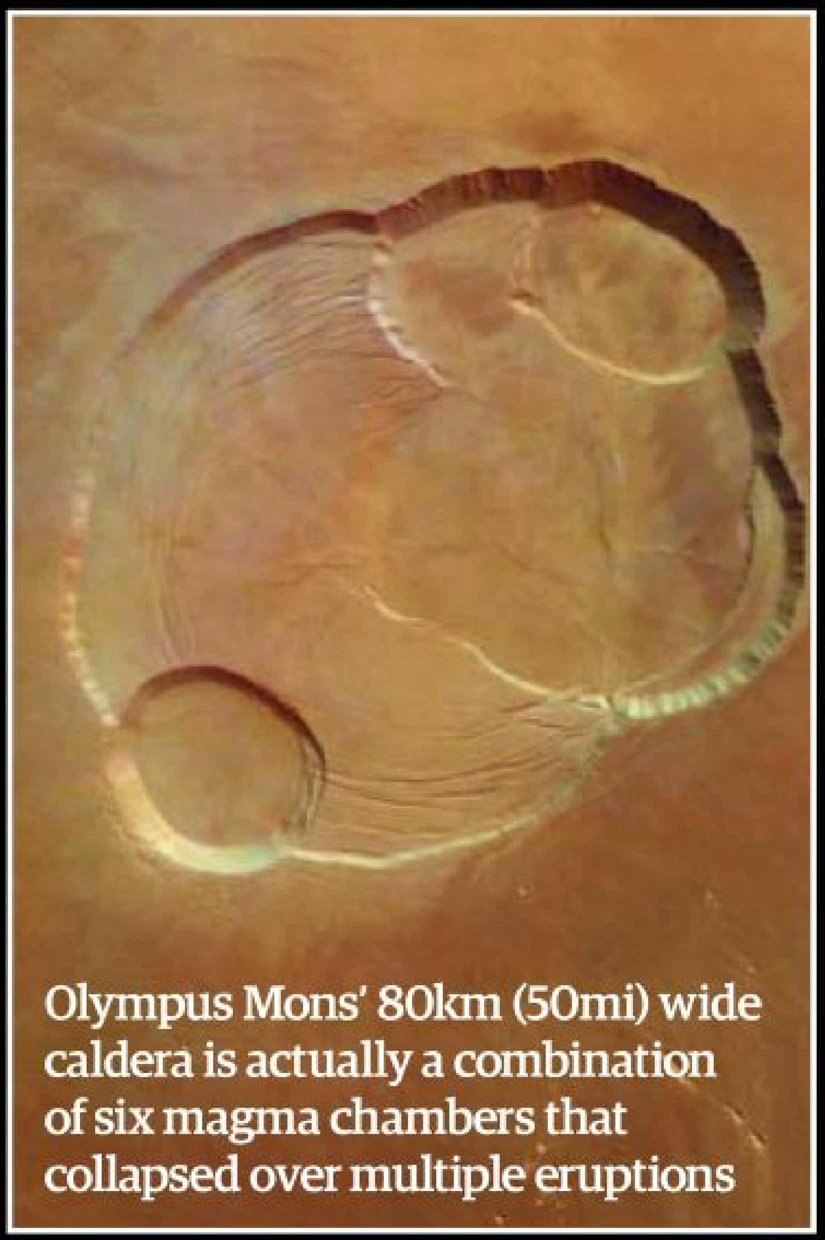
3 Super volcano

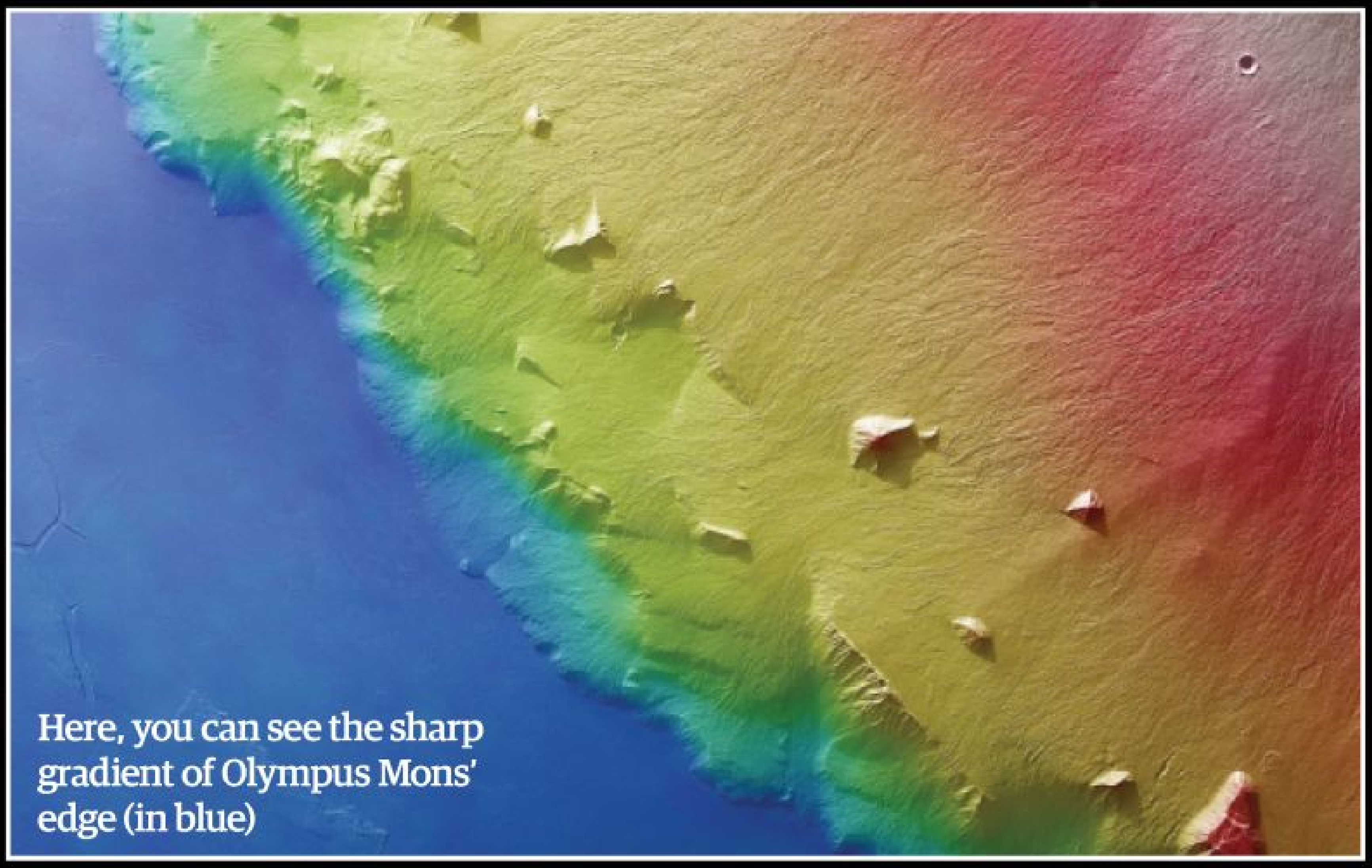
The tallest peak on Mars and in the Solar System

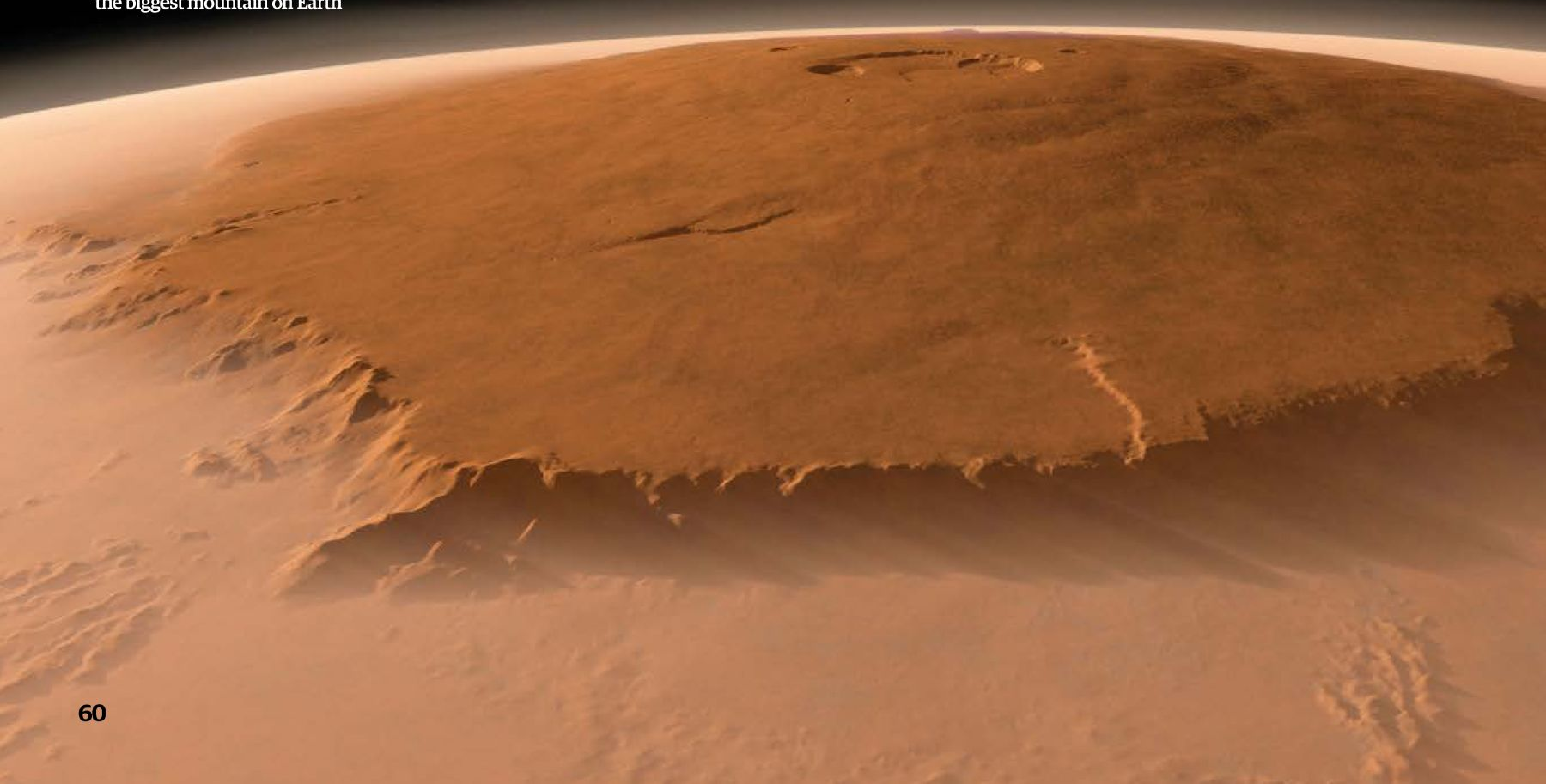
At some point in the distant future, when commercial space flights have reached the border of the asteroid belt and we can freely explore other planets, Olympus Mons will likely become the number one tourist destination in the Solar System, outside of any wonder on Earth. It holds some impressive titles, including the tallest known peak in the Solar System at 22 kilometres (14 miles) from base to tip and a diameter of around 624 kilometres (374 miles), nearly the same size as France and about the same size as the US state of Arizona. It has a caldera to match its enormous expanse: at around 80 kilometres (50 miles) in diameter, these six collapsed magma chambers form a single crater-like depression that's easily large enough to comfortably hold one of the biggest cities in the world by area, New York, with plenty of room to spare. And the volume of Olympus Mons is equally huge at around 100 times that of the Hawaiian volcano Mauna Loa, which is enough to contain the entire Hawaiian archipelago from Hawaii to Kauai, in fact.

This is no mere mountain, however. Olympus Mons is a giant volcano, a shield volcano to be precise, the kind that spews lava slowly down its slopes rather than violently erupting magma, smoke and ash kilometres into the sky. As a shield volcano it has a low profile and its sides slope at an average incline of only five per cent. In fact, if you were standing at the top of Olympus Mons and didn't know it, you probably wouldn't be aware that you were at the summit of a very high mountain. If you walked to the far edge where the volcano begins to rise, you'd encounter an escarpment, or boundary cliff, an astonishing ten kilometres (six miles) high. That's higher than the largest volcano on Earth, Hawaii's own shield volcano Mauna Loa.

Olympus Mons' giant size is no fluke. Low Martian gravity has a part to play in the continuous build-up of cooling lava on its flanks. But tectonic activity on Mars is extremely limited compared to Earth, too: unlike the Hawaiian islands, for example, which have produced several smaller volcanoes as a result of plate movement over millions of years, Olympus Mons has been sitting in the same spot for a long time, allowing the volcano to continuously erupt and grow to its current size.

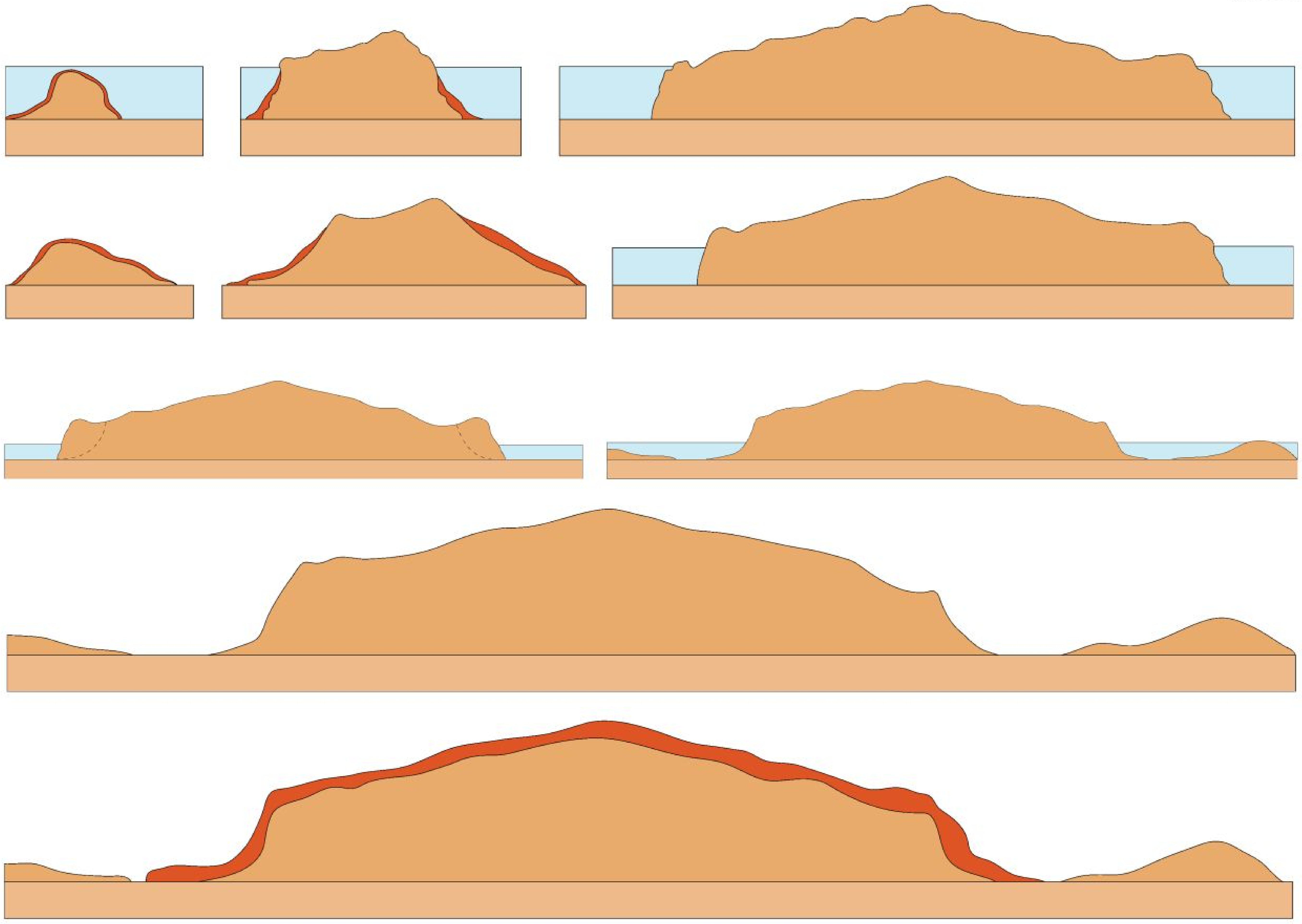

Olympus Mons' 80km (50mi) wide caldera is actually a combination of six magma chambers that collapsed over multiple eruptions


Here, you can see the sharp gradient of Olympus Mons' edge (in blue)


Olympus Mons towers far above the biggest mountain on Earth

How Olympus Mons was created

The theories on how the biggest volcano in the Solar System formed



Subaqua birth
One theory is that lava flowed underwater, piling up until it reached the surface and then spread out sideways after.

Subaerial birth
In the subaerial theory, the lava piled up and flowed in the air, with water rising later to change the dynamics of the lava flow.

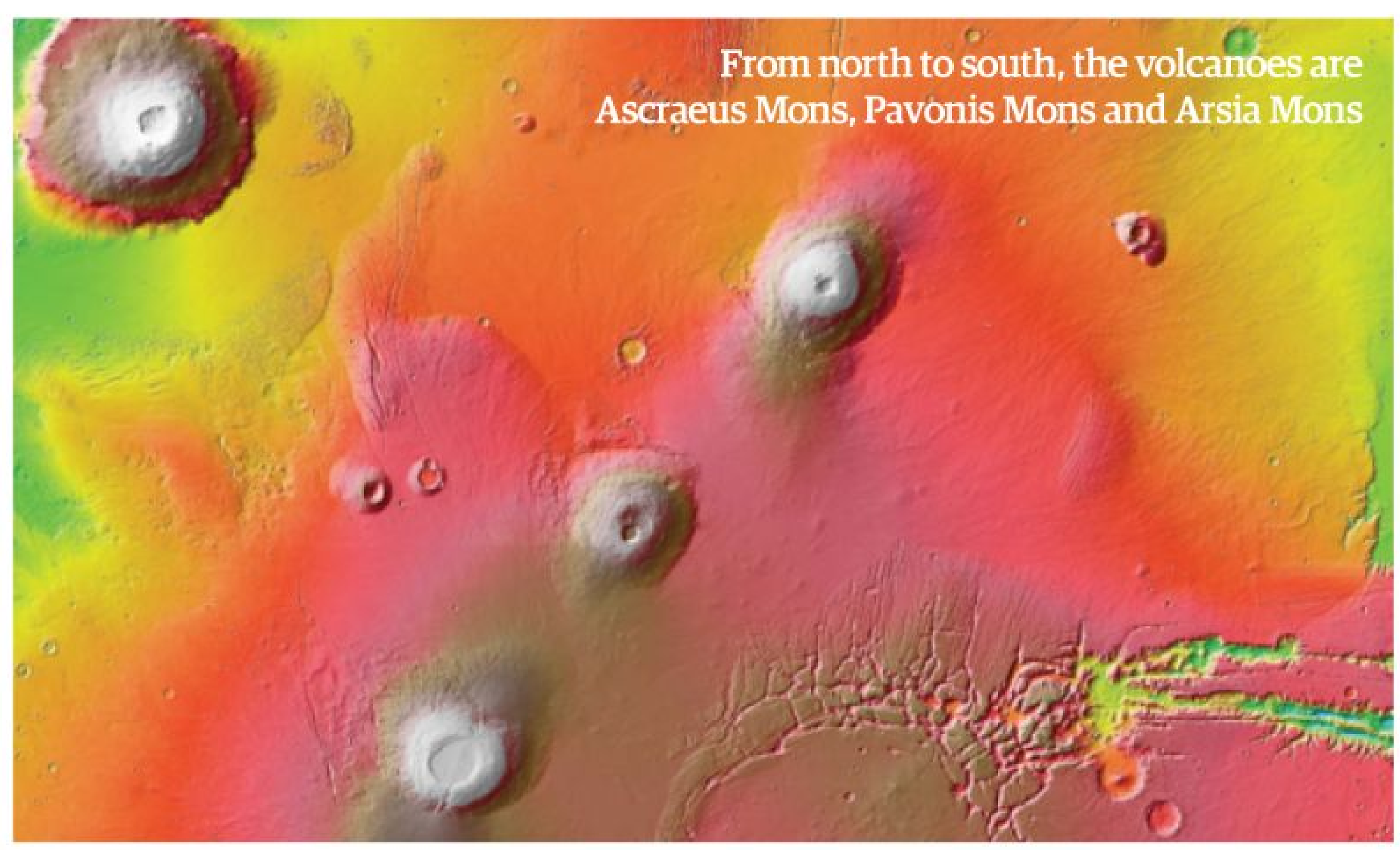
Landslides
Regardless of whether Olympus Mons was partially underwater or not, instability resulted in multiple landslides, reducing its size.

Water drains
As the water drained from the northern lowlands, further landslides shaped Olympus Mons, giving it its lopsided aureole.

New lava
When the water surrounding Olympus Mons disappeared, fresh lava flow smoothed its previously scarred surface.

4 Volcanic hot spot

Tharsis Montes is responsible for Mars's most famous features


From north to south, the volcanoes are Ascraeus Mons, Pavonis Mons and Arsia Mons

Mariner 9 was the first spacecraft to orbit another planet when it arrived at Mars in November 1971, with the Red Planet engulfed by one of its characteristic dust storms at the time. As the orbiter began to return unprecedented close-ups of the surface of Mars to Earth, NASA could make out three faint but distinctive spots. This was the Tharsis Montes region of Mars and the spots were actually the peaks of three enormous volcanoes, evenly spaced in a northeast-southwest orientation. To the northwest, what had been known as 'Nix Olympica' since the 19th Century and was suspected to be a mountain, was discovered to be a massive volcano and was subsequently renamed Olympus Mons.

Tharsis Montes is the biggest volcanic region on Mars: it's some 4,000 kilometres (2,500 miles) wide and is home to 12 huge volcanoes up to 100 times bigger than their equivalent on Earth.

The Tharsis Montes region is responsible for many of Mars's more interesting wonders. Around 4 billion years ago, rising magma caused what is now a plateau to rise, forming the Tharsis bulge, a geological feature the size of North America. This led to the formation of Valles Marineris, the Tharsis Montes volcanoes and Alba Mons, a huge volcano with a diameter of roughly 1,500 kilometres (930 miles) but with an extremely low relief that makes it unique on Mars. Olympus Mons is often (understandably) attributed to the area, although it's actually not part of the plateau.

5 Martian two-face

The planet-shattering reason behind Mars's strange north-south divide

Sometimes it's hard to see the woods for all the trees, as is the case with the strange, near-hemispheric dichotomy of Mars's southern highlands and northern lowlands. The difference between the two hemispheres has been observed for decades now, with investigation by orbiting probes in the late-Seventies highlighting the radical contrast between the topography of each region: the south is rugged, volcanic and pock-marked with craters and features the tallest peaks in the Solar System, while the north is a huge plain of unparalleled smoothness, with an altitude typically several kilometres below the lower regions of the south. Up until recently no one really knew why this was, although it was known that this feature was very ancient, almost as old as the planet itself.

A few theories had been postulated as to why the two halves were so different: one was that convection in the mantle caused upwelling in the south and downwelling in the north. The other, originally proposed in 1984, was that the hemispheric dichotomy was the result of a single enormous impact. It was the simplest solution to the mystery that meant the entire northern region, an area 8,500 kilometres (5,300 miles) wide and 10,600 kilometres (6,600 miles) long, was a colossal impact basin. That theory quickly got shot down because the borders of the northern hemisphere didn't fit the expected round shape of an impact crater.

However, since the Eighties, several confirmed craters have been discovered with strangely elliptical borders, such as the Moon's South Pole-Aitken basin. The case for the massive impact theory wasn't helped by the fact that the Tharsis bulge and its enormous volcanoes formed after this huge crater was created, obscuring the shape of the rim on one side. So it was only after two decades of surface and gravitational field observations by various spacecraft that the unambiguously elliptical impact basin of the northern hemisphere was revealed.

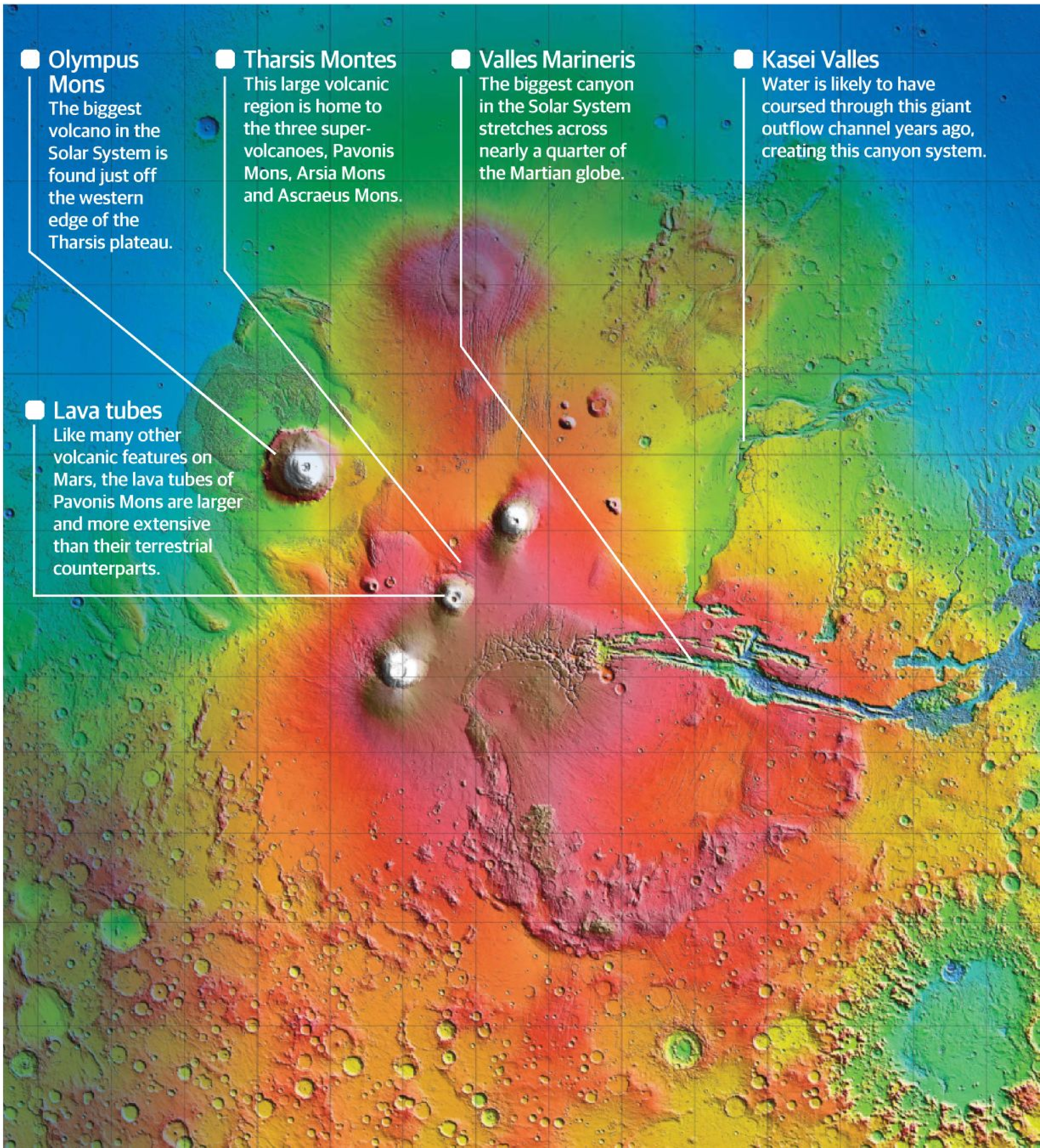
Today, although the giant impact theory hasn't been proved beyond doubt, the evidence weighs heavily in its favour. The Borealis Basin, if it is the result of an ancient impact, will be the largest known crater in the Solar System: covering an area of around 90 million square kilometres (35 million square miles) it's larger than the continents of Europe, Australia and Asia combined. That's

Mapping the surface of Mars

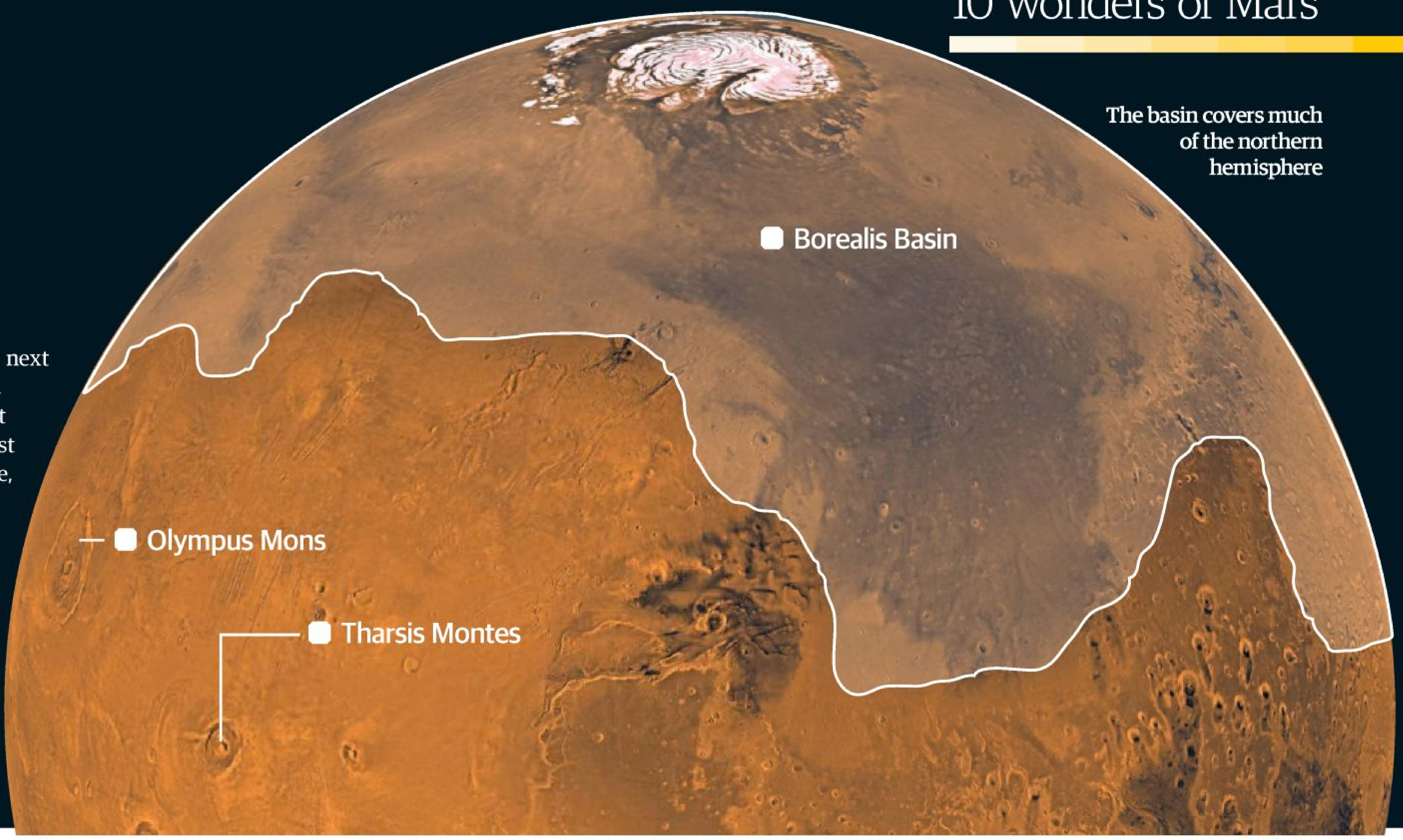
The Mars Global Surveyor was sent to orbit Mars with the expressed goal of doing the job of a terrestrial surveyor, but on an enormous scale. Among its major missions (which included surveying the Martian atmosphere and interior), it was tasked with mapping the entire Martian surface and geology with the aim of providing the foundations of future NASA missions for years to come.

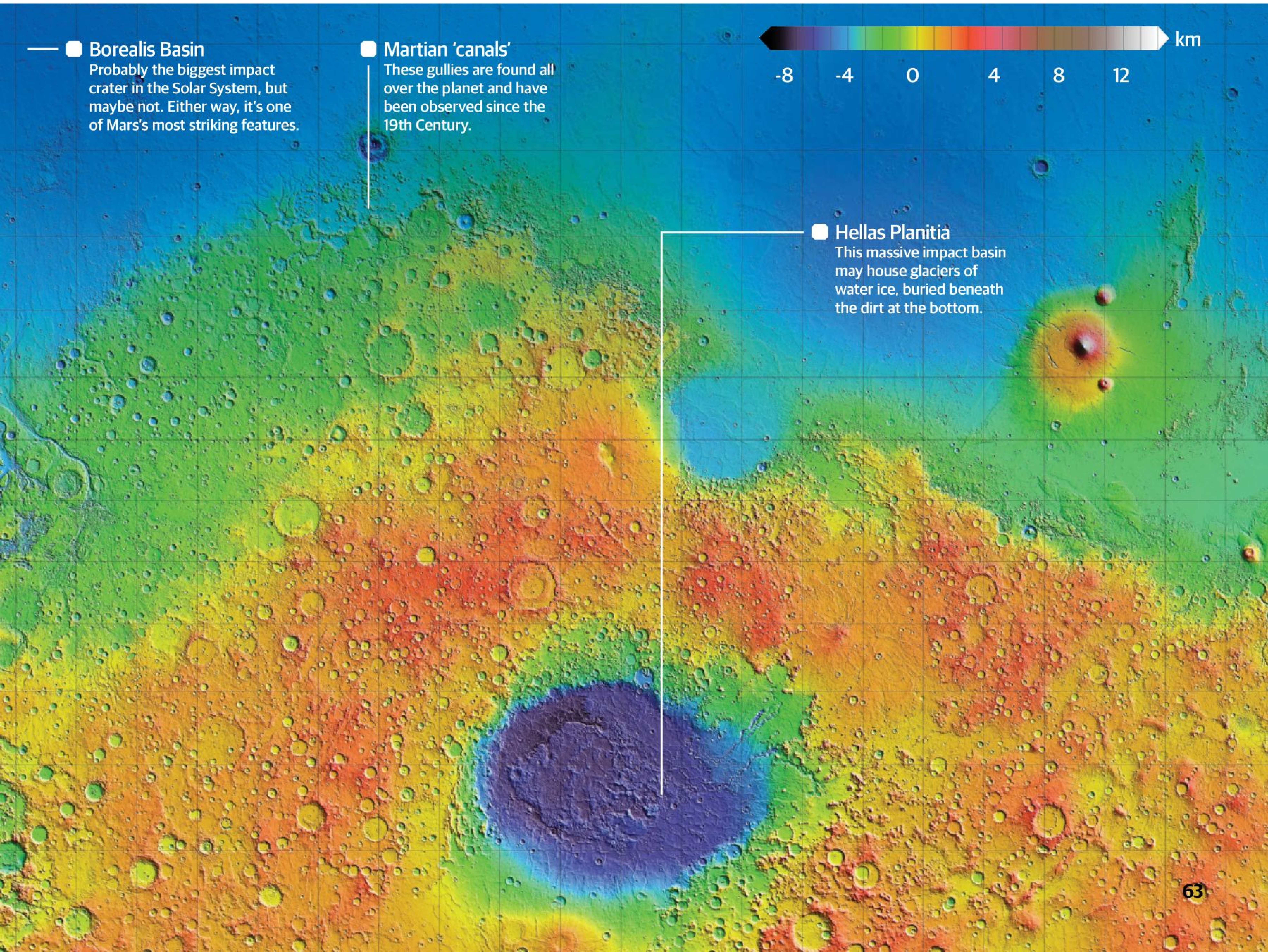
Using the Mars Orbiter Laser Altimeter (MOLA) this mission was phenomenally successful, creating a flat, high-resolution map from over 640 million elevation measurements assembled into a global grid with an accuracy that ranged from 13 metres (42 feet) to within two metres (six feet). The map is so accurate and complete that it gives us a better knowledge of Martian topography than some continental areas of Earth.

The findings of this survey include the discovery of Mars's full topographic range, which is about one and a half times that of Earth and goes from the deepest trough in the Hellas Impact Crater to 30 kilometres (19 miles) higher at the tallest point of Olympus Mons. The Mars Global Surveyor also gave us a much clearer idea of the dynamics of water on the surface of the Red Planet, with the huge difference in elevation between the northern and southern hemispheres meaning that the lowlands of the north would have drained around three-quarters of the surface of Mars, at an earlier period in Martian history when water could have flowed freely on the surface.



nearly four times as big as the next biggest known crater on Mars, Hellas Planitia. The object that created the Borealis Basin must have been terrifyingly massive, around 2,000 kilometres (1,200 miles) in diameter, striking at an angle of 45 degrees to create the elliptical basin. These objects and collisions were relatively common 4 billion years ago, shaping the geography and the orbits of the planets to mould the Solar System as we know it today.





6 Giant dust storms

The enormous clouds of fine red dust that can sometimes grow to engulf the entire planet

The surface of Mars is covered in dust far finer than the sands of any desert on Earth – indeed it's the iron oxide (rust) content of this dust and the underlying rock that gives the planet its distinctive ruddy colour. From month to month, the gentle Martian winds blow clouds of dust across the landscape, stripping the surface sands away to reveal underlying rock in some places, and accumulating in other places to form spectacular dunes.

Normally, these billowing dust storms flare up and die away in a couple of days, but occasionally they can grow in size to the scale of entire continents before subsiding. And every couple of years, around the time of Mars's closest approach to the Sun, they can run out of control to wrap the entire planet in an orange murk that persists for several months.

These enormous storms are only possible because of the size of Martian sand – the Red Planet's thin atmosphere (exerting just one per cent of the Earth's atmospheric pressure) means that even the strongest winds of around 120 kilometres per hour or 75 miles per hour (equivalent to hurricane force on Earth), would barely be able to shift Earth-sized sand grains. But atmospheric dust grains on Mars, worn down by billions of years of steady erosion, are comparable in size to the particles in cigarette smoke, so that even the gentle winds of the planet's thin atmosphere can lift them from the ground. Wind speeds in a typical storm are around 100 kilometres per hour (62 miles per hour), but an astronaut on the surface would barely feel that as a light breeze.

Once lofted into the air, dust particles may linger for months. The reasons for this persistence are still uncertain, but it's possible that weak electromagnetic fields help to repel them from each other and prevent them settling back on the ground. This means that once the dust particles are stirred up, they can move at speeds many times faster than those in dust storms on Earth, and travel much further. As they absorb sunlight and prevent it from reaching the surface, atmospheric temperatures may rise by up to 30 degrees Celsius (86 degrees Fahrenheit).

Awesome though they may appear, the main threat from storms to either current Mars rovers and landers, or future astronauts, comes from the dust they carry within them. As it settles back out of the atmosphere it may coat equipment and solar panels with particles that get into delicate mechanisms and cut down the efficiency of solar panels. Fortunately, NASA engineers have discovered that encounters with the occasional 'dust devils' that spiral across the Martian surface can also help remove dust and restore power.

> "Dust storms can wrap the entire planet in an orange murk for several months"

The air is so thin on Mars, an astronaut would barely be able to feel this raging storm

In June 2001, the Hubble Space Telescope captured this crystal-clear image of Mars, highlighting clouds around its north and south poles

Three months later, as Mars approached perihelion, a planet-wide dust storm blocked Hubble's view of everything but the bright polar caps

Storm cycles

Major dust storms are typically most common around Martian perihelion (the planet's closest approach to the Sun). Because the orbit of Mars, unlike that of the Earth, is distinctly elliptical, it receives up to 40 per cent more sunlight around this time, which helps to create strong temperature differences across the planet that in turn generate high winds. Unfortunately for earthbound astronomers, perihelion is also the best time to view Mars, so the Red Planet is frequently engulfed in clouds around the time when it is at its largest and brightest in Earth's skies. Even space probes are not immune to the problem – in fact Mariner 9, the first space mission to enter orbit around Mars, arrived during a major dust storm in November 1971 and had to wait for about a month until the atmosphere cleared and it was able to send back the first detailed photographs of the Martian surface.

7 Subterranean lava tubes

A hidden world of caves that could shelter Martian microbes

Rising to about 12 kilometres (7.5 miles) above the surrounding dusty plains, Pavonis Mons is roughly three kilometres (1.9 miles) higher than Everest. However, it has another feature that qualifies as a Martian wonder in its own right.

Running down the volcano's southwest flank are a number of parallel, tadpole-shaped features that look at first like empty riverbeds. Tens of kilometres long, their heads point roughly towards the volcano's summit, while their tails peter out or merge to form broader depressions.

But these valleys are not the work of water erosion. Known as 'lava tubes', they form when the surface of a lava flow starts to cool and solidify, but molten rock continues to run below the surface. When the eruption finally comes to an end, the underground river of lava may drain away completely, leaving behind a cavernous subterranean passage.

Normally, lava tubes are all but invisible from the surface, but over time, the weight of overlying rock may cause their ceilings to cave in, creating steep-sided valleys like the ones seen on Pavonis Mons. In other places, the surface may just subside to form a string of circular depressions known as a pit chain. When the middle of the depression then collapses inward, the result is a 'skylight' opening into the lava tube.

When the first astronauts reach Mars, they may head straight for these curious portals. Lava tubes offer natural protection from the harsh surface environment, and are an obvious place to set up a long-term base. And for the same reasons, they are also one of the most promising places to look for simple Martian life.

A skylight – or entrance – to a lava tube on Pavonis Mons

This perspective view of Pavonis Mons from ESA's Mars Express Orbiter reveals circular pits dotted among the longer, fully collapsed lava tubes

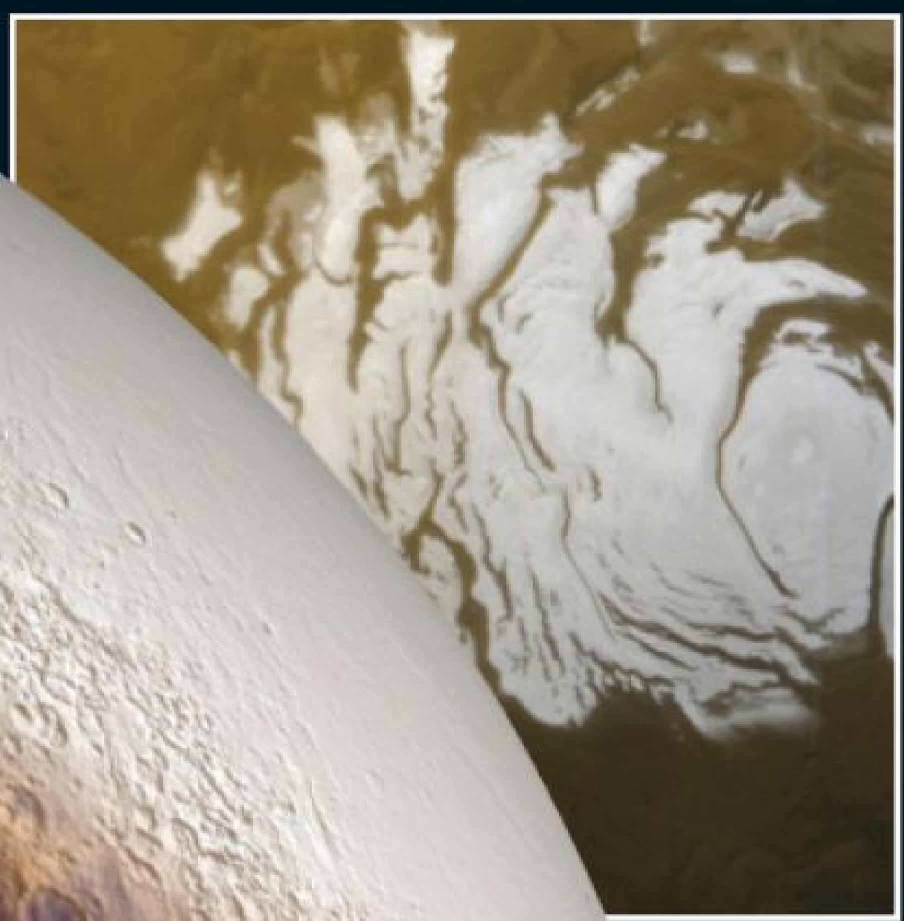
8 Frozen carbon dioxide poles

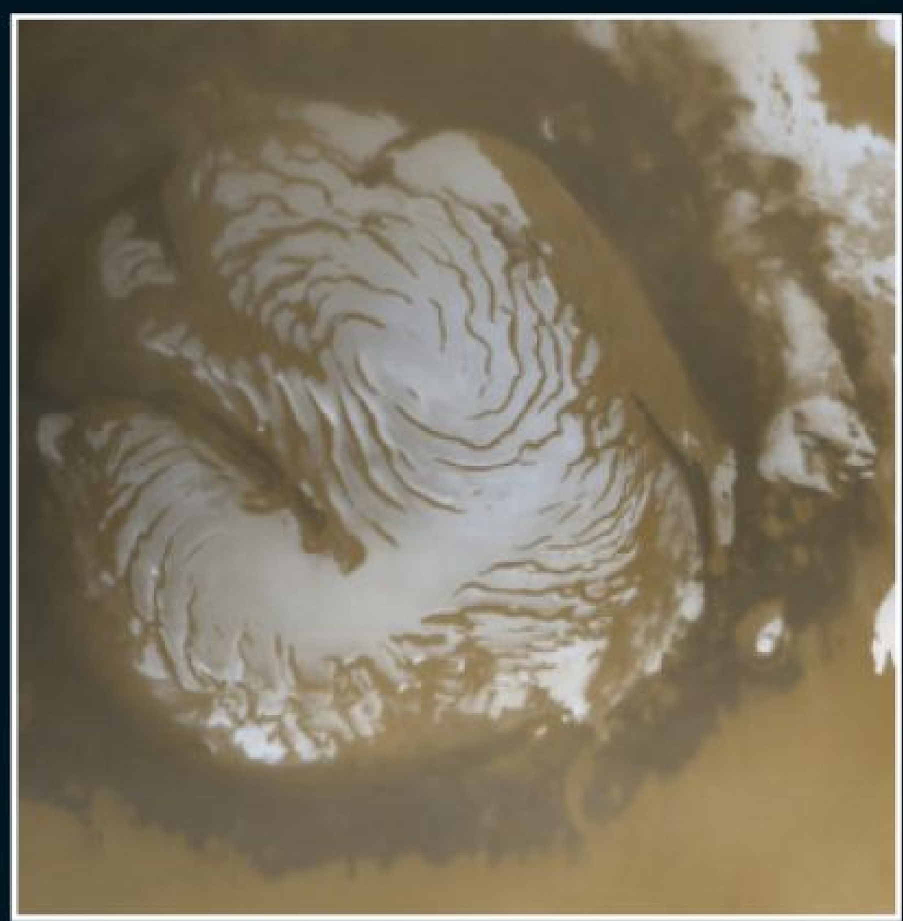
Mars has two permanent ice caps, but they're not like Earth's poles…

The temperature at the Martian equator is probably not as bitter as you might think, pushing the mercury as high as 20 degrees Celsius (68 degrees Fahrenheit) during the summer, with a soil temperature that has been recorded close to a positively beachy 30 degrees Celsius (86 degrees Fahrenheit). It's a different story at the poles, however: with a desperately thin atmospheric pressure of just 600 pascals to insulate them – a fraction of Earth's 101,000 pascals – little heat is retained at either end of the Red Planet. Here, temperatures have been known to drop to as low as -153 degrees Celsius (-243 degrees Fahrenheit) in the complete darkness of a Martian polar winter.

The Martian caps are pretty puny compared to those on Earth. The biggest of the two, the northern ice cap, has an estimated volume of 1.6 million cubic metres (56 million cubic feet), while the Antarctic ice sheet, the biggest on Earth, has a volume of 26.5 million cubic metres (935 million cubic feet). However, the extreme cold at the Martian poles results in over a quarter of Mars's atmosphere freezing into enormous slabs – and because over 95 per cent of Martian air is carbon dioxide, winter brings a deposition of up to two metres (6.5 feet) of dry ice. When summer comes around, rising temperatures cause the frozen carbon dioxide to sublimate (turn immediately from solid to gas) and return to the atmosphere. The changes in the amount of carbon dioxide in the atmosphere, along with the increasing and receding poles during summer and winter, is so great that the gravitational field of Mars changes with the seasons as a result.

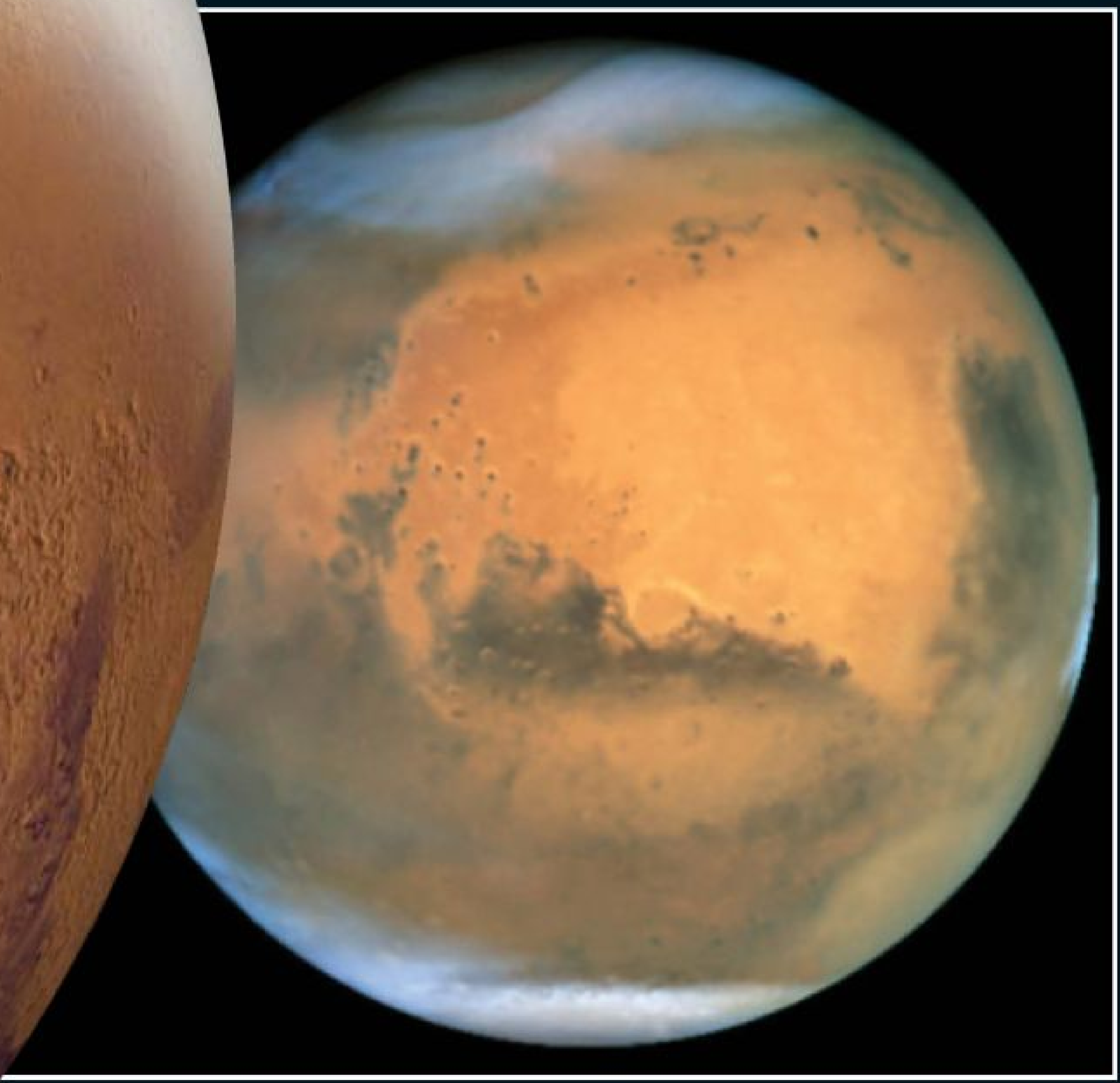
Mars also experiences ice ages across a time scale of hundreds of thousands of years, caused by marginal changes in its orbit and axial tilt. Like Earth it's currently in an interglacial period, but from around 2.1 million to 400,000 years ago, a time when sabre-toothed cats, woolly mammoths and other Pleistocene megafauna roamed Earth, Mars was plunged into an ice age of its own. The increased tilt on its axis heated the poles, evaporating ice into the atmosphere only for it to settle and spread from the 60 degree latitude mark to around 30 degrees north of the Martian equator in both hemispheres.





The Martian north pole (right-hand image) can get even colder than the south (left) in a Martian winter, and reaches temperatures as low as -153°C (-243°F)

Mars during its ice age over 400,000 years ago. The ice caps reached the equivalent latitudes of Mexico in the north and Australia in the south



The Martian polar caps are shown in this Hubble image of the Red Planet taken in 2001. A huge dust storm can also be seen at the northern cap

This massive impact basin can easily be seen from Earth

9 Deep impact

The huge Martian crater that's visible from Earth

Hellas Planitia is a huge crater that was formed in the early days of the Solar System, an era of heavy meteorite bombardment around 4 billion years ago when enormous objects flew around and collided with others on a regular basis. With its bright, reflective floor it's a spectacular site, even when viewed from Earth.

It has a diameter of 2,250 kilometres (1,400 miles) and over nine kilometres (5.6 miles) separate the rim of the crater from its floor. The rims are nearly two kilometres (1.2 miles) high, which puts the floor of the basin seven kilometres (4.3 miles) below what on Mars would correspond with sea-level on Earth. At this depth, the atmospheric pressure at the bottom is nearly double that at the top. Under certain conditions, that's enough for liquid water to form. There's evidence to suggest that the gullies around the basin rim were formed by glacial movement as well as explosive boiling of the water into steam.

Hellas Planitia would be the biggest crater on Mars, if it wasn't for the suspected (but still unconfirmed) Borealis Basin in Mars's northern hemisphere.

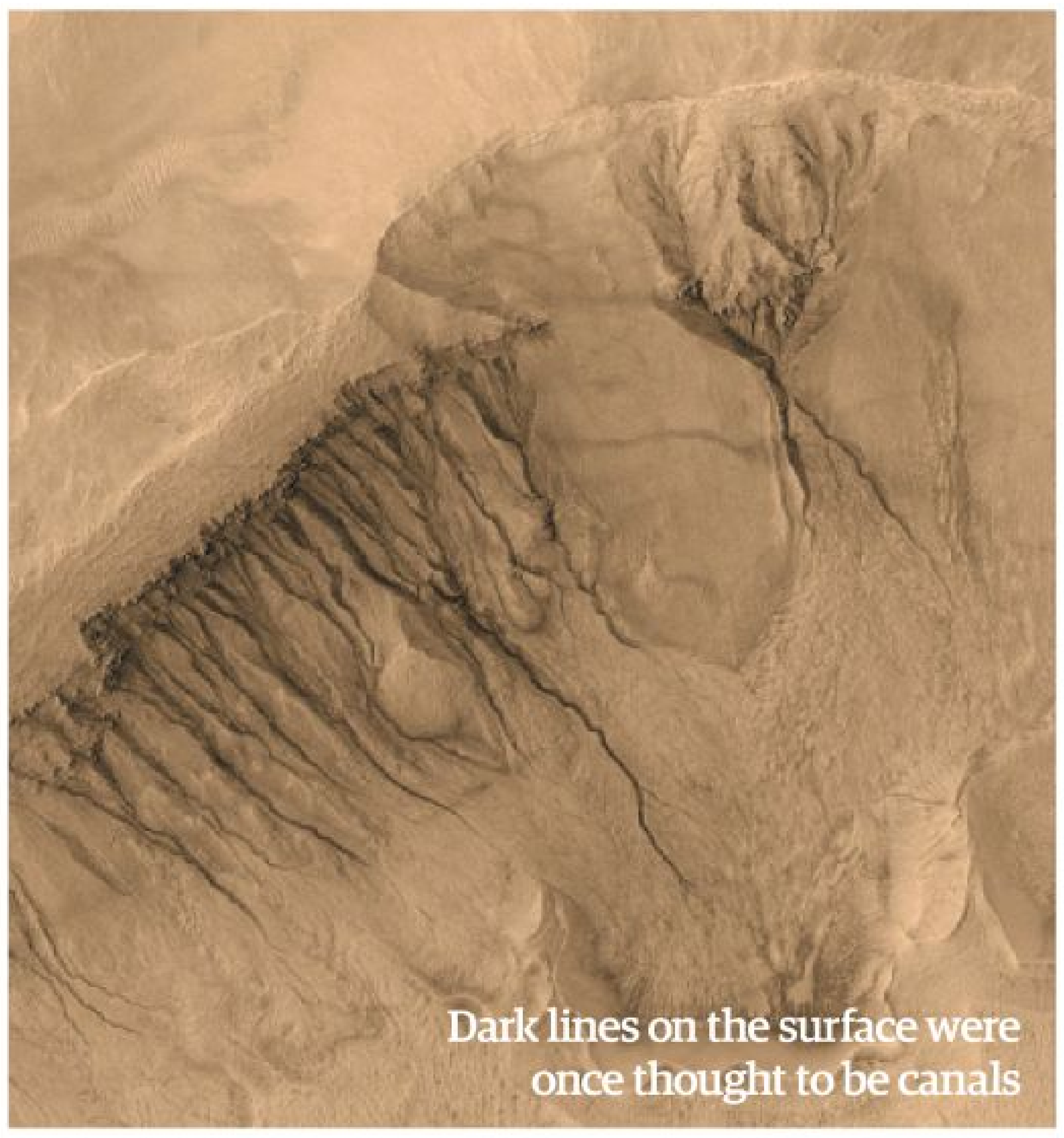
10 Martian 'canals'

The features that went on to inspire a century of science fiction

In 1877, astronomer Giovanni Schiaparelli observed numerous gullies criss-crossing the surface of Mars, which he described in his native Italian tongue as 'canali'. For better or for worse, the literal translation of 'canals' was made into English and from there, early 20th Century academics (including a certain Percival Lowell), flushed with the prominence of a new scientific age, promptly assumed that evidence of an intelligent civilisation was inferred.

Fortunately, others were more scientific in their observations, pointing out that the 'canals' were caused by an optical illusion in poor-quality telescopes that joined visible features by lines. Spectroscopic analysis showed that atmospheric pressure on Mars was indeed too low for liquid water and that the Red Planet was considerably colder than originally anticipated. Finally, powerful telescopes of the day showed no such lines on Mars, which led to this rather tenuous theory quickly being debunked, although the notion of a Martian civilisation lived on in science fiction for decades.

Today, albedo features – the craters and basins like Hellas Planitia that contrast the russet background, as well as dust streaks leading across mountains and dust storms – can be considered the remains of what were once the great Martian canal system.



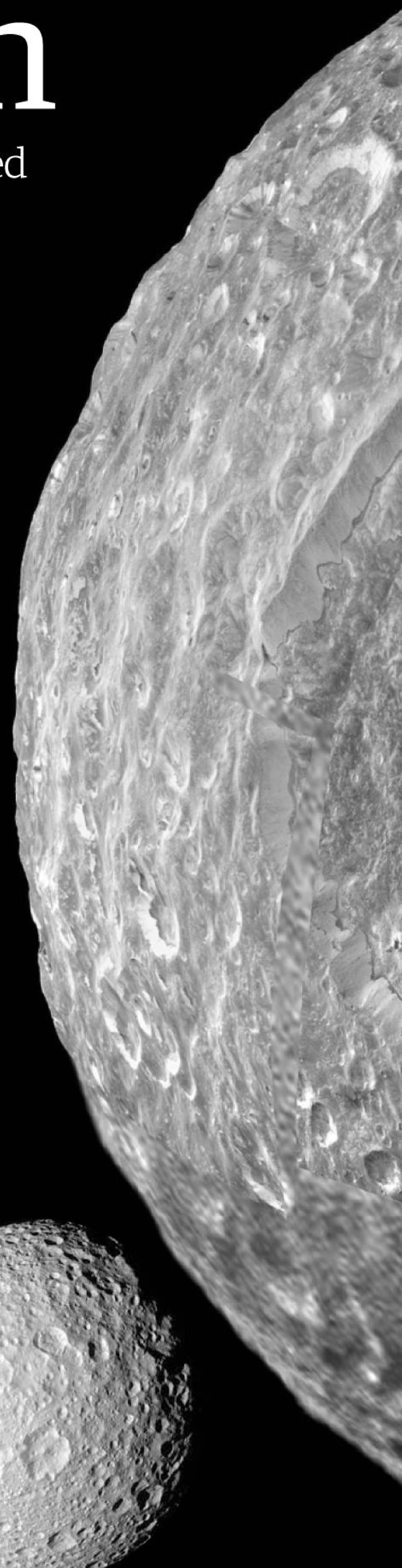
Dark lines on the surface were once thought to be canals

Are we Martians?

The theory of panspermia, that an asteroid bearing the 'seeds' of life impacted the Earth aeons ago, isn't a new one. But following a major scientific conference in Italy recently, the idea that life on Earth may have originated from Mars, is picking up some serious traction. We don't know exactly how the building blocks of life came about, the RNA, DNA and amino acids that were brought together to form the prebiotic 'soup', but we're pretty sure that RNA was there first. On Earth, the minerals necessary for creating the RNA template would likely have dissolved in the oceans, but that wouldn't have been the case in the relatively arid environment of ancient Mars. The theory, outlined by Professor Steven Benner of the Westheimer Institute for Science and Technology, is that these minerals oxidised on Mars, eventually forming RNA. This was then transported to Earth and deposited via one or possibly many meteorites (Martian meteorite strikes are still very common today), conceiving the first life on Earth.

Death Star moon

This small Saturnian moon is one of the most heavily cratered bodies in the Solar System, including one massive impact…



Cassini's causing quite a stir with the images and data it's returning from a certain moon of Saturn these days. But the buzz around Enceladus, and the confirmation of a watery ocean beneath the crust of ice on its surface, has taken our attention away from some of Saturn's other notable satellites. This is despite the fact it's the contrast between Mimas and Enceladus that make both particularly interesting.

Mimas is a somewhat oblate (squashed spheroid) moon that is an average of 397 kilometres (247 miles) in diameter. It's also a pretty low-density object of around 1.17 times the density of liquid water, which suggests that most of this moon is made of water ice, with a small proportion of rock, frozen solid at a temperature of around -209 degrees Celsius (-344 degrees Fahrenheit). This caused an interesting problem for scientists, because not only is Mimas closer to Saturn than Cassini's current favourite target, Enceladus, but it has a more-eccentric orbit that should subject the moon to the greater tidal heating of Saturn's powerful gravitational field.

Geologically speaking Mimas is dead, while Enceladus is still spouting great geysers of water ice into its atmosphere, along with a range of organic compounds. This paradox of Saturn's moons has been explained, in part at least, by the higher density of Enceladus, which likely has a much greater rock content. It's thought that Enceladus' liquid interior and Mimas' solid body are explained by the same theory.

Mimas' permanently frozen state has persisted for billions of years, probably since it was formed. The evidence for this is the dense population of impact structures on its surface, rivalled by few other objects in the Solar System. A sister moon, Rhea, has a comparable number of craters to Mimas, but has no single feature quite as impressive as the enormous Herschel crater. With a diameter of around 140 kilometres (87 miles), walls five kilometres (three miles) high and a floor ten kilometres (six miles) deep, this is by far the biggest crater on this tiny satellite.

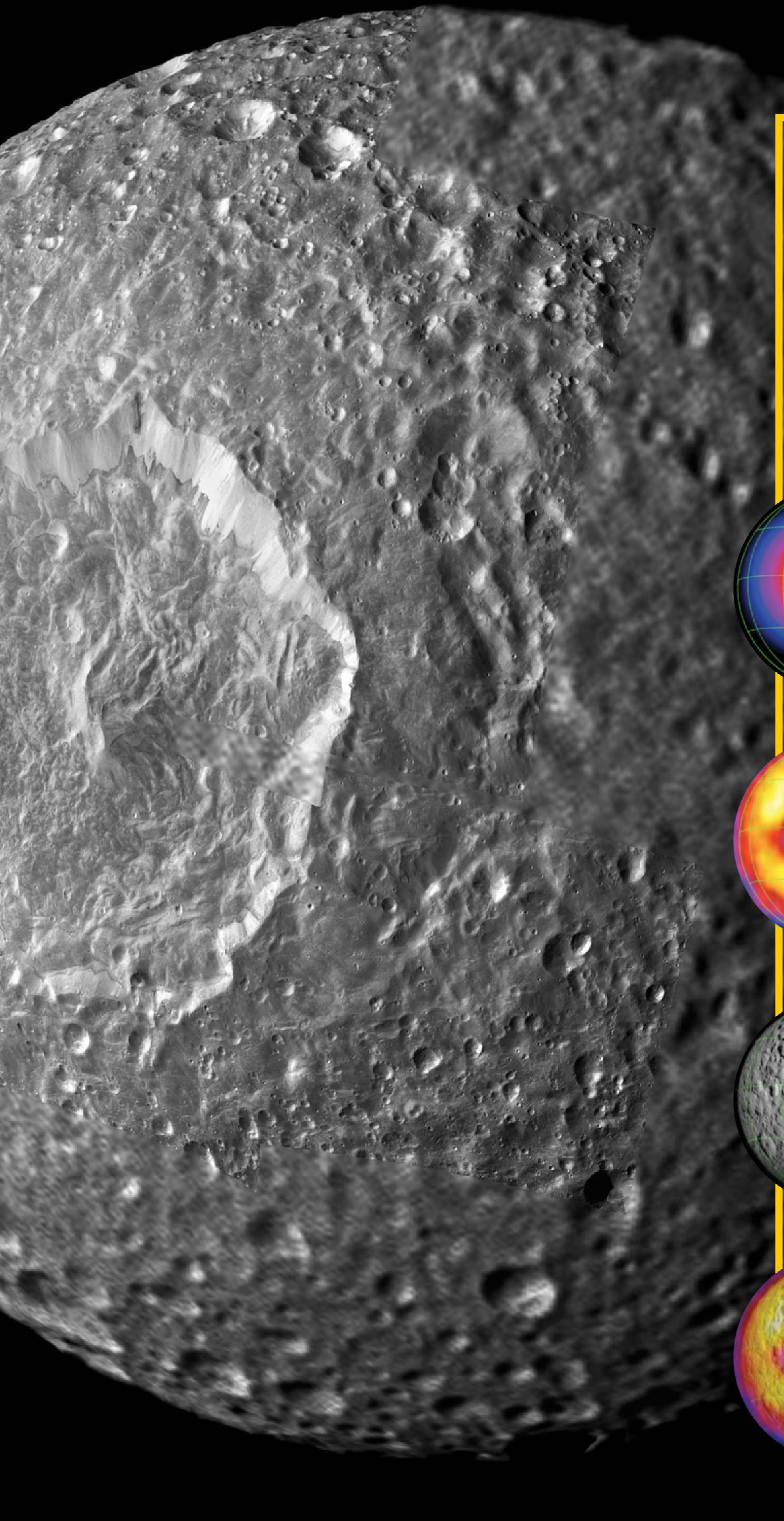
Proportionally, it's one of the biggest impact structures in the Solar System, too. From rim to rim, it's spread across one third of the face of Mimas: if Earth had an equivalent crater, it would stretch around 4,000 kilometres (2,500 miles) wide and have walls over 200 kilometres (124 miles) high. It's a wonder that the impactor that created this crater didn't smash Mimas into fragments, because its legacy literally runs deeper than the 4.1 billion-year-old crater it left behind.

The enormous energy of the impact must have travelled as a shockwave through Mimas to the other side, where massive stresses on the surface cracked open into chasmata, like the Ossa Chasma. The impact likely played a role in the strange temperature pattern of Mimas, which bears an uncanny resemblance to the classic videogame character Pac-Man. Herschel's other legacy to pop culture is also pure coincidence: from certain angles, in images taken both by Cassini and Voyager 1, it looks distinctly like the Death Star from *Star Wars Episode IV*. Voyager 1 discovered Herschel three years after the film was made, so Mimas couldn't have inspired the fictional super weapon.

The moon is also responsible for clearing most of a huge region in Saturn's orbit, creating a 4,800-kilometre- (2,980-mile-) wide gap between two of Saturn's widest rings, A and B. This is known today as the Cassini Division.

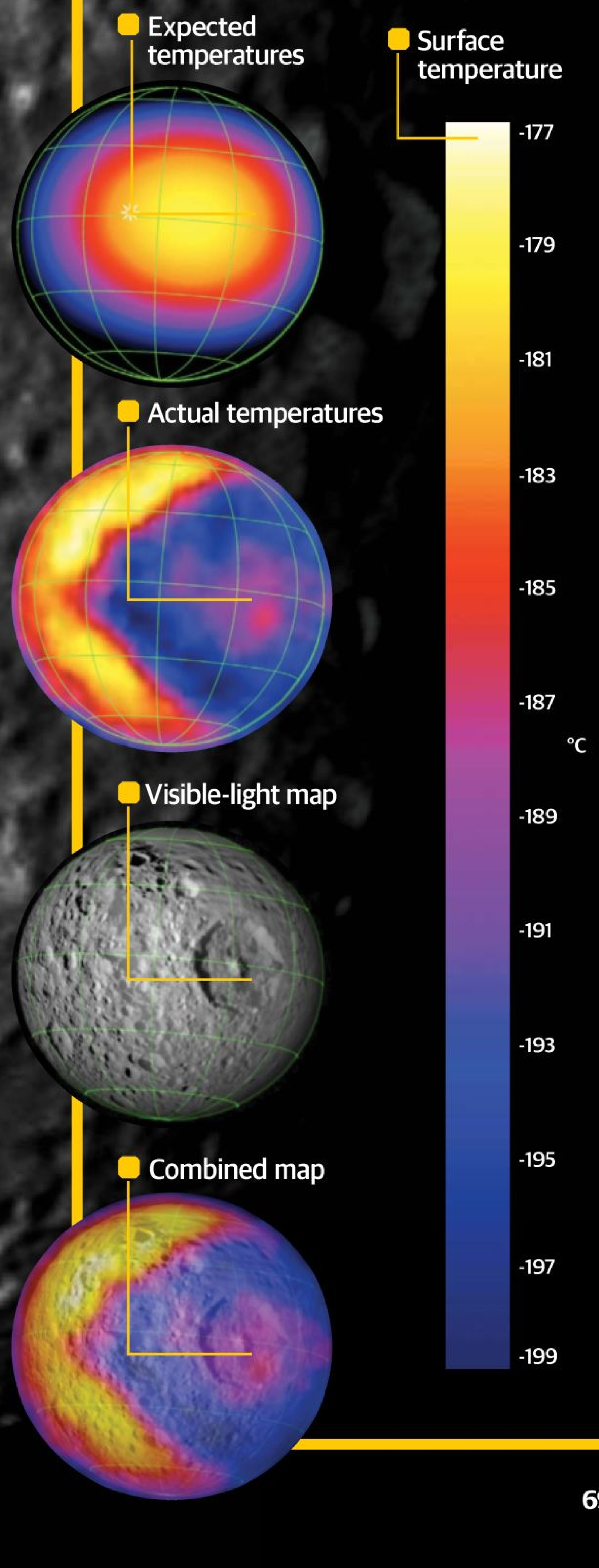
> "Geologically speaking Mimas is dead, while Enceladus is still spouting great geysers of water ice into its atmosphere"

Images taken by Cassini show the different faces of Mimas' heavily cratered surface



Pac-Man Moon

Cassini's composite infrared spectrometer returned an unexpected image to the team at NASA in 2010. Instead of the expected, smoothly decreasing temperature pattern radiating out from the moon's core, Cassini showed a V-shape thermal image for Mimas with a sharp drop-off on the opposite side of the Herschel crater. The cold part of the image is explained by the greater thermal conductivity of materials on the surface of that side, but scientists don't know why it varies so dramatically. With Herschel as the power pill, this thermal image does make Mimas look very much like Pac-Man.



Lunar caving

We're ready to explore a cave recently found on the Moon – but how do we do that and what will we find?

It seems appropriate that, having left our caves over a million years ago in the pursuit of improving the quality of life for our species, we're now looking to return there for more or less the same reasons. This isn't on Earth of course, but on the Moon.

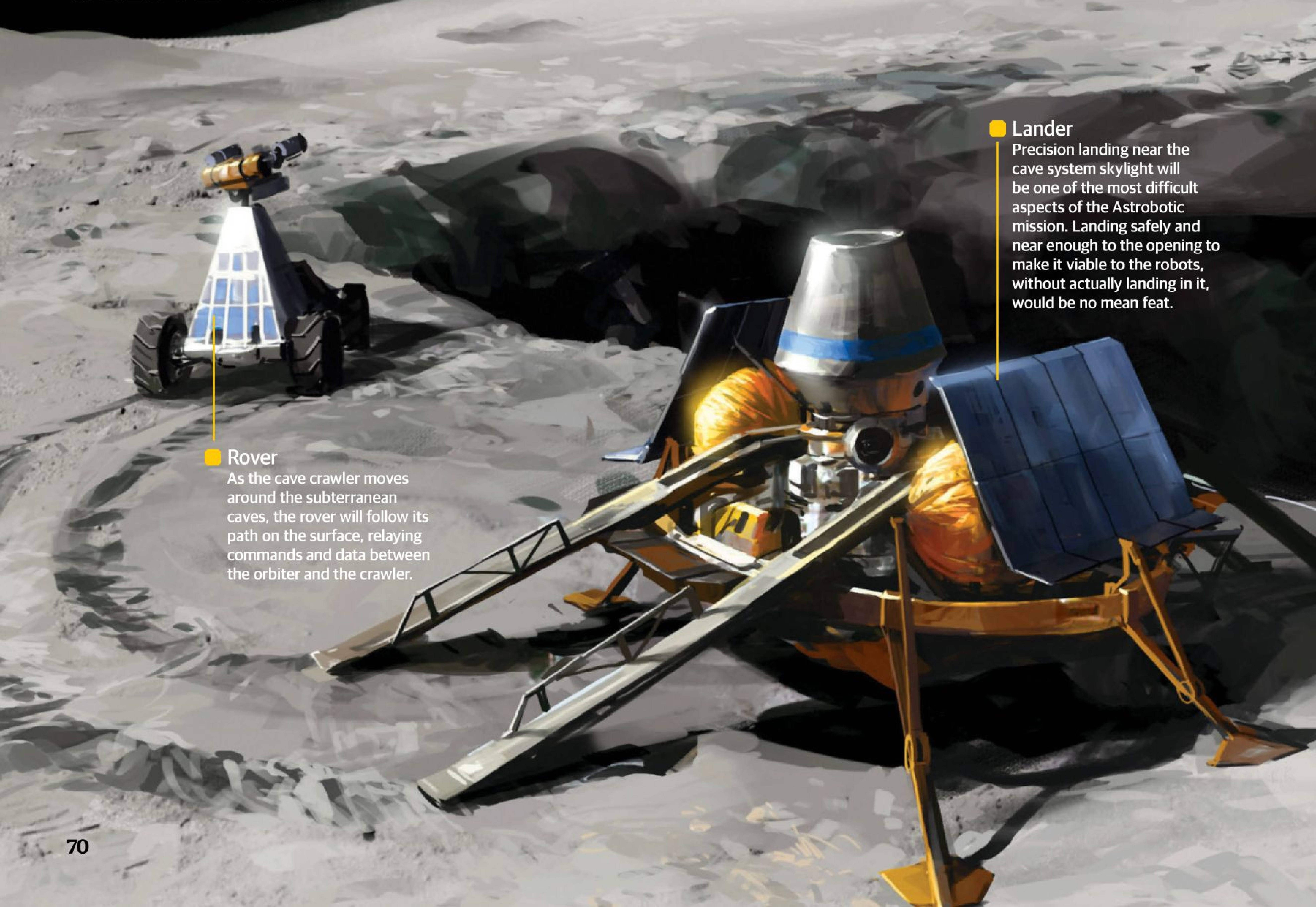
In 2009 a team of Japanese researchers led by Junichi Haruyama discovered a hole in the Marius Hills region on the near side of the Moon. This area is known for its ancient volcanism and is lined with long channels known as sinuous rilles. It's thought these were formed by lava that once flowed on the surface or through lava tubes.

The tubes and rilles are nothing to get excited about – evidence of this kind of geological activity can be found on other planets in the Solar System, including Mars. This hole is something special though – it isn't another crater formed by the impact of a meteorite or comet. After imaging the hole several times the team was able to calculate that it was 65 metres (213 feet) wide and 88 metres (289 feet) deep. In other words, it was deeper than it was wide, dimensions that are impossible for an impact crater. Also, it couldn't been the empty caldera of a long-extinct volcano, because there's no evidence of either ash or lava around the hole. This had to be the entrance to a cave, most likely a tunnel collapse on a lava tube with an estimated 370 metres (1,214 feet) of tunnel extending either side of the opening.

So, there's a cave on the Moon, what's the big deal? Let's set aside the insatiable desire we have for exploration that drives us to poke our noses into strange places (even though that's what got us into space in the first place) and look at the scientific merits of sending a mission to this phenomenon.

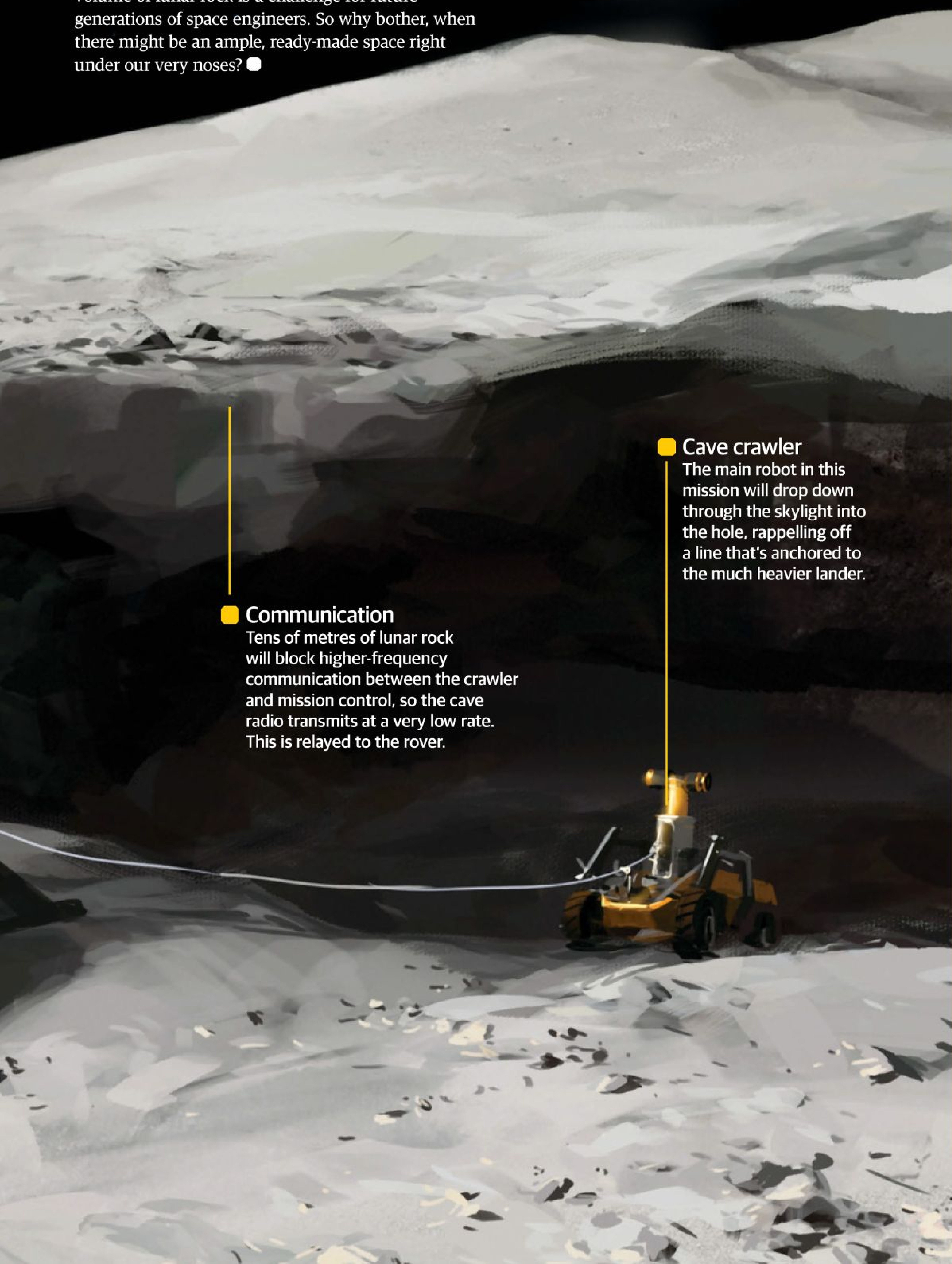
This cave could be a bit of a geological wonderland, giving us an unprecedented insight into the inner workings of the Moon, where hundreds of kilometres of these tunnels carrying rivers of lava ran beneath the lunar surface billions of years ago, emptying into the vast maria we can see from the Earth. It's possible that, since the lava flows have cooled and solidified, emptying out of the tubes, research into their formation could be conducted to ascertain their potential for collecting water on Mars. The Moon has no atmosphere, oceans or any life to disturb conditions in the lava tubes, so makes a better analogue to Mars than similar tubes found on Earth. Ultimately, investigating this lunar cave may

How to explore a Moon cave

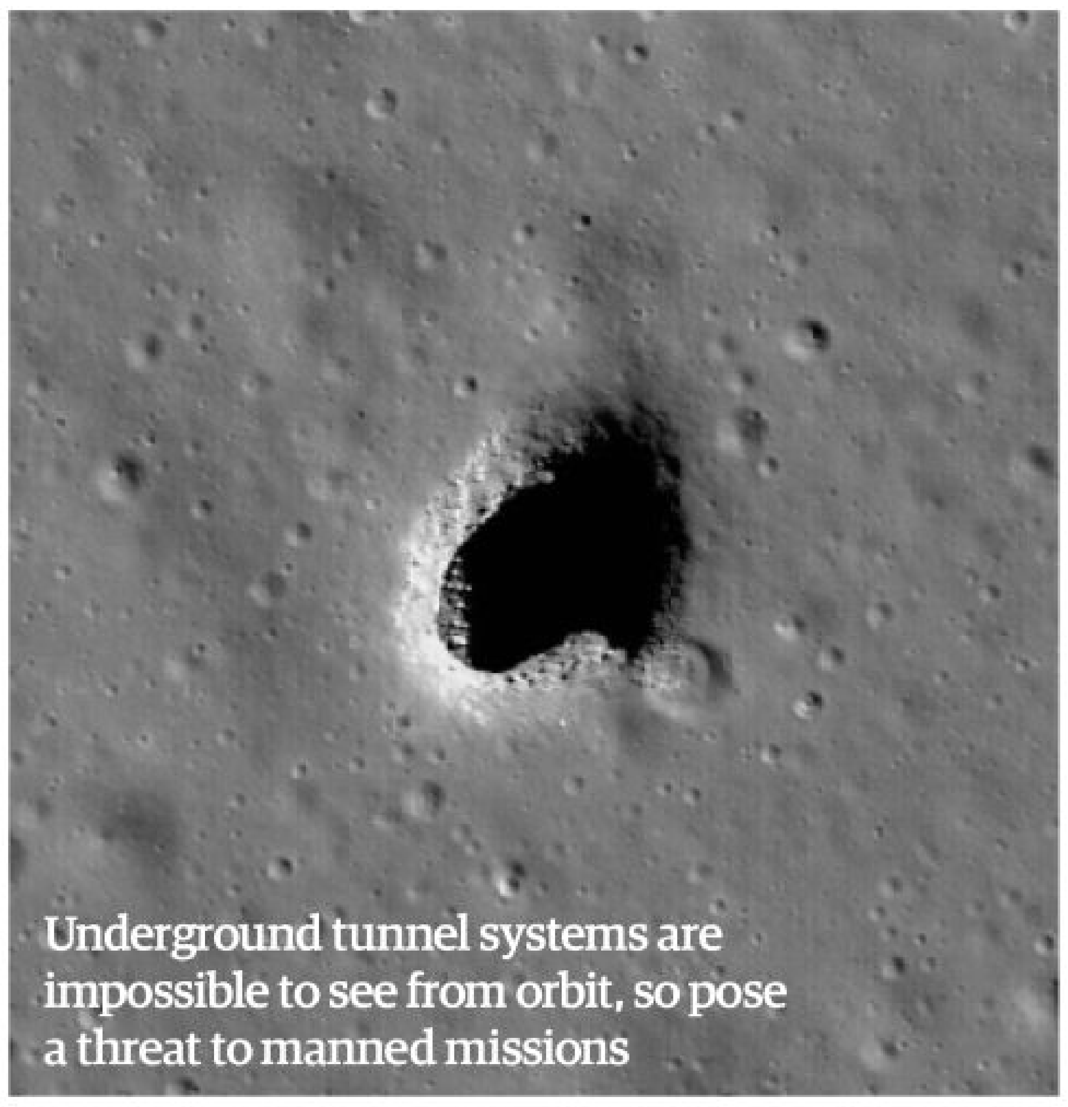


better prepare us for an investigation into whether life could have existed in comparable tubes on Mars.

These tunnels could also be very cavernous in places and provide an ideal plot for a lunar base. The surface of the Moon is regularly bombarded with radiation and fluctuates wildly in temperature, from highs of over 100 degrees Celsius during the day and lows of less than -150 at night (212 to -238 degrees Fahrenheit). But the lunar surface itself is an excellent shield against deadly cosmic rays and solar radiation. Just two metres (6.6 feet) down, the temperature levels off to a fairly constant -30 to -40 degrees Celsius (-22 to -40 degrees Fahrenheit). You might think that we could dig this hole ourselves, of course, but setting up a construction site on the Moon with a view to excavating an enormous volume of lunar rock is a challenge for future generations of space engineers. So why bother, when there might be an ample, ready-made space right under our very noses?



Robot spelunker


Underground tunnel systems are impossible to see from orbit, so pose a threat to manned missions

Before we pack up the camping gear and send an expedition to create an outpost on the Moon, we'll need to scout out Haruyama's cave – with robots of course. These tunnel systems can't be seen from orbit, so pose an unknown and unacceptable risk to any expensive expedition using astronauts. Technologically speaking, we're practically ready to send a robotic probe into the cave, however.

Pittsburgh-based private space exploration company and Google Lunar XPRIZE competitor Astrobotic already has a mission in development, scheduled to drop rovers on the Moon that will then explore Haruyama's cave and any others like it. These will relay data about the cave to the surface and from there back to Earth. From this data, we should be able to construct a three-dimensional model of the interior as well as determine whether a manned mission is feasible.

IMPACT ON JUPITER

Relive the explosive meeting between planet and comet that gripped the world's media 20 years ago

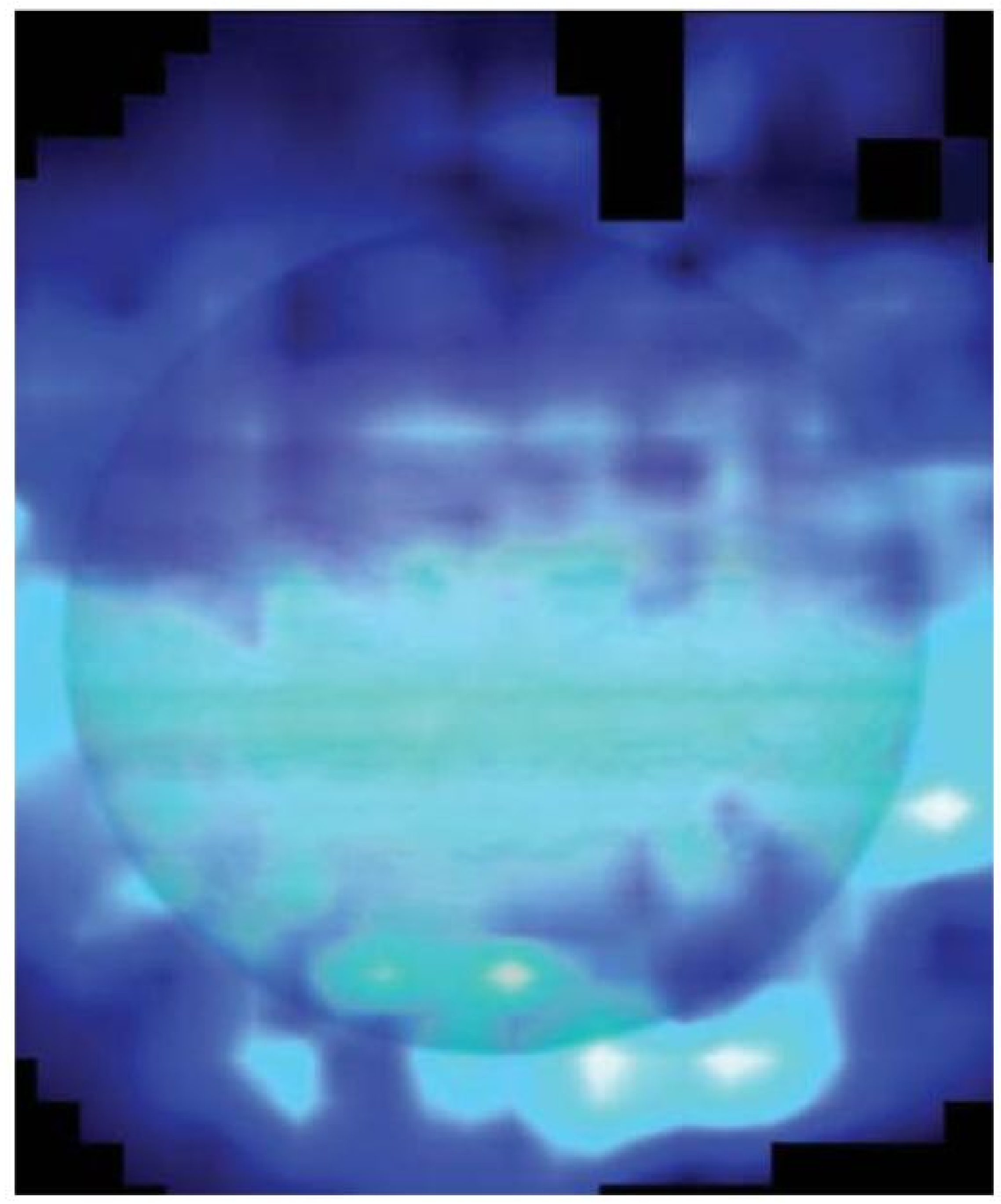
Comet Shoemaker-Levy 9 was the comet that dared to strike the king of the Solar System. It's true that Jupiter takes the brunt of the Solar System's wayward debris, colliding with its gaseous bulk, but this event was nothing that the astronomical community had ever witnessed in the past or could have anticipated.

It all began during a hunt for space rock on a potentially deadly collision course with our planet, in a program that intended to get to these dangerous near-Earth objects before they got to us. Astronomers trusted the 0.4-metre (1.3-foot) Schmidt telescope at the Palomar Observatory with this important task. Snapping away at the night sky, the Californian telescope tirelessly stood sentry night after night. Its photographic findings were later pored over by astronomers in a bid to detect the one object that could wipe us out, whether it was an asteroid or comet. On the evening of 24 March 1993, three astronomers – Eugene and Carolyn Shoemaker alongside David Levy – were poring over one particular image produced by Palomar, and what they found defied all expectations. Carolyn was originally scanning the images that the three had taken that night, when she found what she felt was an oblate, comet-like object.

This turned out to be Comet Shoemaker-Levy 9, their ninth periodic comet, whose orbital period took less than 200 years. However, this wasn't what was so unusual about it. Its squashed appearance was telling the astronomers something important: that Shoemaker-Levy 9 wasn't orbiting the Sun. Instead it had been captured by the merciless and monstrous gravitational pull of Jupiter and now its nucleus was fragmenting in response to its precarious approach to the gas giant's limbs. It's thought that in July 1992, at an altitude of only 25,000 kilometres (16,000 miles) over Jupiter's cloud tops and cutting well within the orbit of its innermost moon (Metis), the tidal forces got heavy-handed on the comet's delicate structure and began to rip it apart. Experts speculated that the comet had been caught around 20 to 30 years previously, so Shoemaker-Levy 9 had done well to stay in shape up until this point.

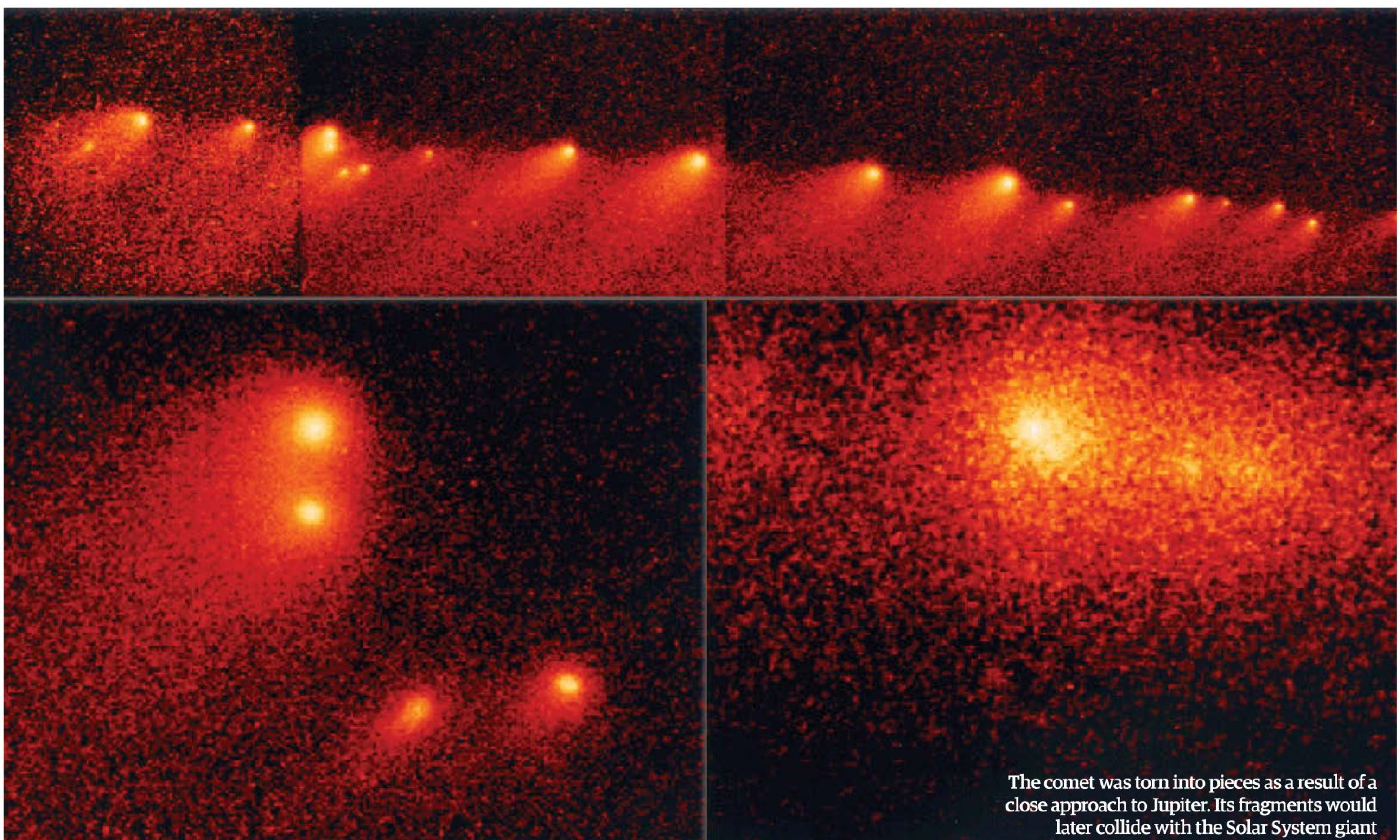
On 22 May, the same year of their discovery, Levy and the Shoemakers would learn of their comet's fate: Shoemaker-Levy 9 was going to end its life by diving into Jupiter's atmosphere. It would impact the planet in many pieces, ranging from a few hundred metres all of the way up to two kilometres (1.2 miles) in diameter. As soon as they found out there was going to be a collision, the three comet-watchers knew it would be a historic comet.

This point of view wasn't shared by all astronomers, however. Some considered Shoemaker-Levy 9 to be a kind of celestial dud and that it was being over-hyped, simply because Jupiter is hit by

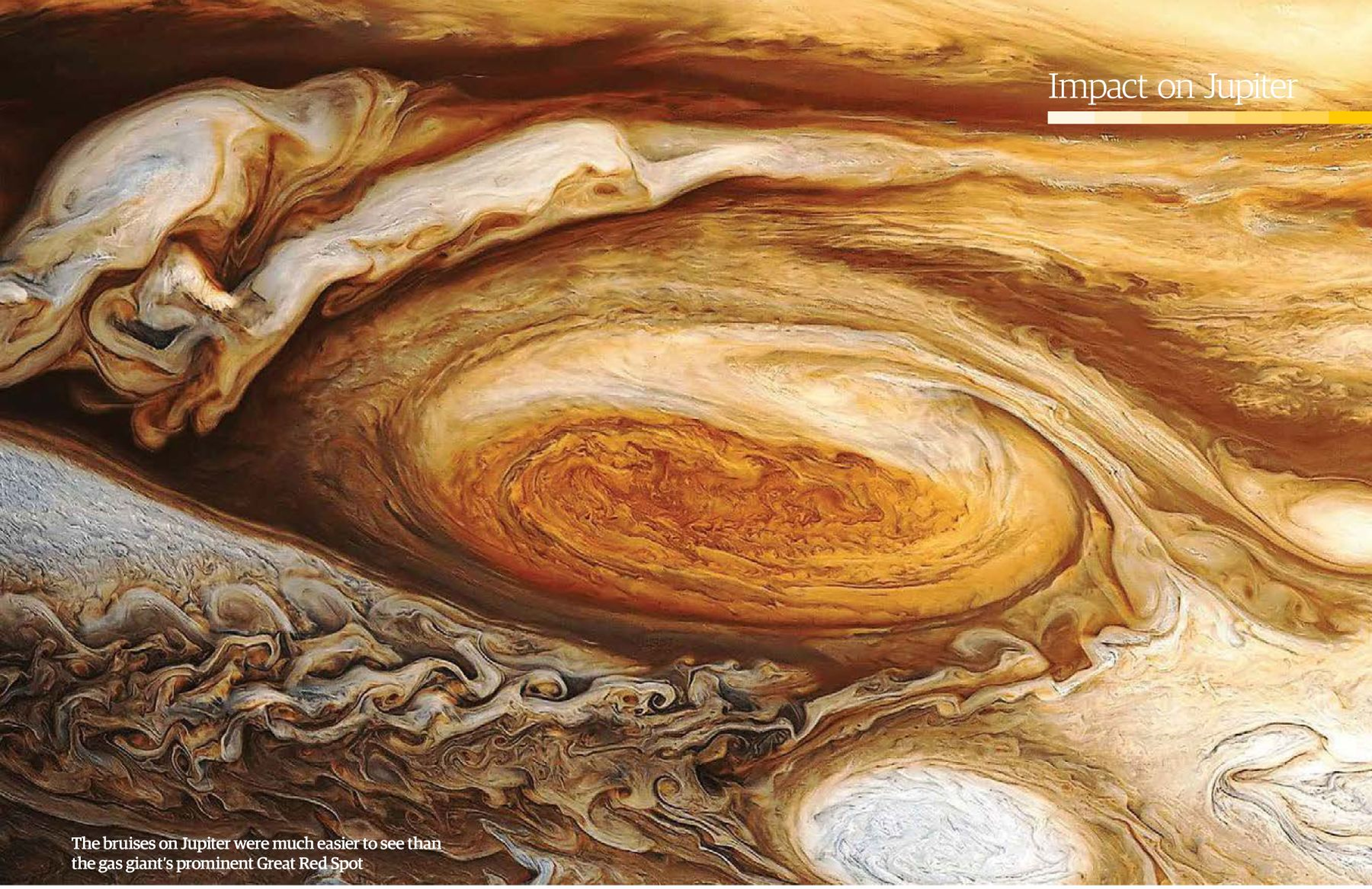


Data from ESA's Herschel Space Observatory showing the Shoemaker-Levy 9 impact could explain why Jupiter has so much water in its upper atmosphere

"The dark spots left across the face of Jupiter were plain to the eye and even more prominent than the planet's famous Great Red Spot"



The comet was torn into pieces as a result of a close approach to Jupiter. Its fragments would later collide with the Solar System giant


The bruises on Jupiter were much easier to see than the gas giant's prominent Great Red Spot

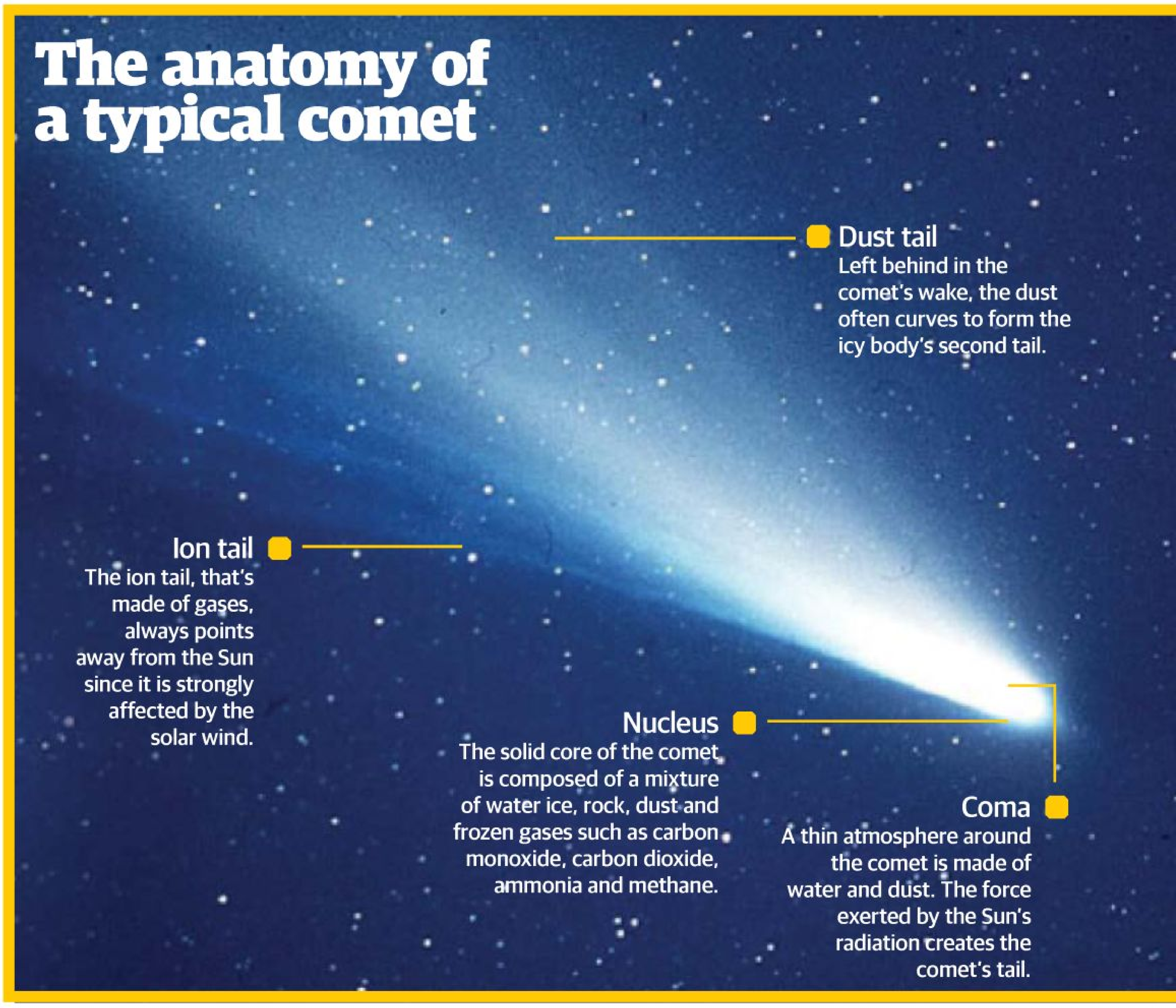
objects all the time, yet nothing happens. What they didn't reckon on was the size of this 'dud': nothing the scale of this fragmented comet had ever hit the gas giant within human memory.

Despite the scepticism, the majority of the astronomical community was watching with bated breath as July the following year arrived. This was the month the various pieces of Shoemaker-Levy 9, labelled fragments A through to W, wheeled in on a path that was destined to hit the giant gas planet's southern hemisphere.

On 16 July 1994, the first fragment crashed in through Jupiter's atmosphere, as telescopes all over the world looked on. Several space-based observatories were also fully focused on the event, such as the Hubble Space Telescope, the ROSAT X-ray observing satellite and also the Galileo satellite, which was on its way to the gas giant at the time. The battering that Jupiter received lasted a whole week, leaving dramatic marks on its surface that made the planet's greatest swirling storm system, the Great Red Spot, pale in insignificance. This iconic feature of Jupiter, for a while, became a second-rate tourist attraction when compared with the trail that Comet Shoemaker-Levy 9 left behind.

Levy himself, by this point, was standing in a long line to the Naval Observatory on the grounds of the American vice president's residence in Washington, hoping to use its telescope to see the impacts his comet had made. When he got in to look through the telescope he was amazed at what he was seeing – the dark spots left across the face of Jupiter were plain to the eye and even more prominent than the planet's famous Great Red Spot.

The anatomy of a typical comet



The planet was so black and blue from the pummelling, that it took close to a year for it to heal. This gave astronomers enough time to work out what extra data the event could yield, that some had previously doubted would be so significant. What lay beneath the cloud tops was revealed when the fragments punched their way through the planet's upper layer at a speed of 60 kilometres (37 miles) per second, like fireballs, ejecting plumes and heating the surrounding jovian gases. The most impressive impact that made the largest mark on the face of Jupiter was fragment G. It created a gigantic dark spot over 12,000 kilometres (7,456 miles) across, and was estimated to have released around the same energy as the world's combined arsenal of nuclear explosives 600 times over. But that's not all that astronomers learned - they also got to know the gas giant much better than ever before.

A closer look at the planet revealed the very first detection of diatomic sulphur, providing only the second finding in any astronomical object, as well as carbon disulphide. Jupiter's make-up was worked out quickly as more molecules such as ammonia were uncovered in the upper atmosphere, while others, such as those carrying oxygen, were nowhere to be seen - much to the surprise of astronomers. A myriad of other molecules were also found much later after the impact, including water in large quantities.

The fragments of Shoemaker-Levy 9 that had bypassed Jupiter's monstrous magnetic field created enormous waves that swept across the planet at speeds of around 450 kilometres (280 miles) per second. Auroral emissions blasted through the gas giant's atmosphere and the planet's temperature raced temperamentally up and down around the impact sites for a good two to three weeks after the event.

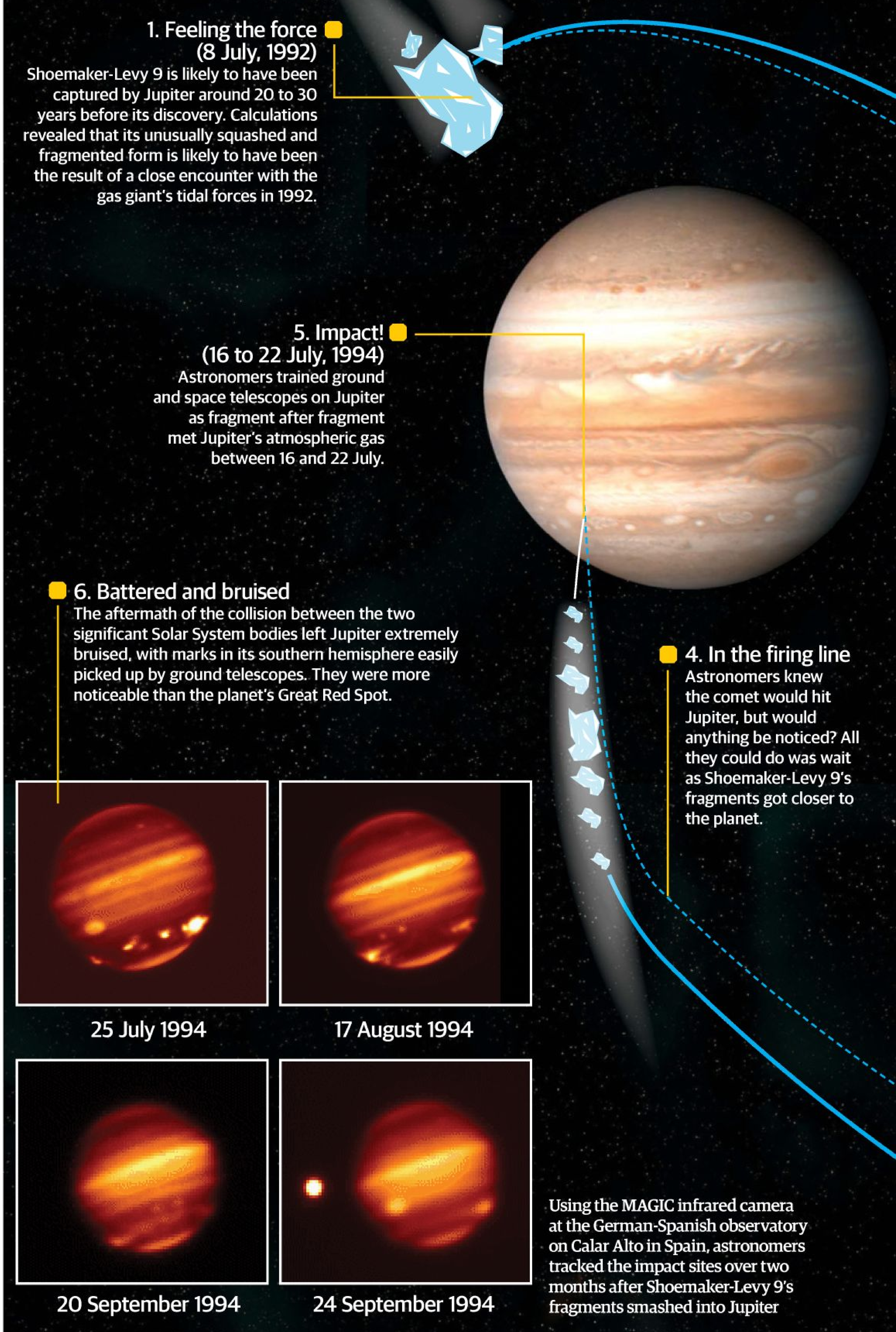
Since the demise of Shoemaker-Levy 9, the tell-tale signs of Jupiter getting struck have not gone unnoticed and have prompted astronomers to keep a close eye on the great planet's next move. Professional and amateur astronomers alike were not disappointed as 2009, 2010 and most recently 2012 saw Jupiter once again take hits. Bolides and asteroids crashed through its upper layer, creating fresh markings that raised the question of whether Jupiter is in fact protecting Earth and keeping us out of harm's way.

The truth is, we just don't know for sure whether or not Jupiter acts as our guardian planet. It could be that the gas giant creates as many potential objects on an apocalyptic trajectory as it sucks up, or maybe its great gravitational attraction has hoovered up the majority of stray comets or pieces of space debris, as it acts as the celestial goalkeeper.

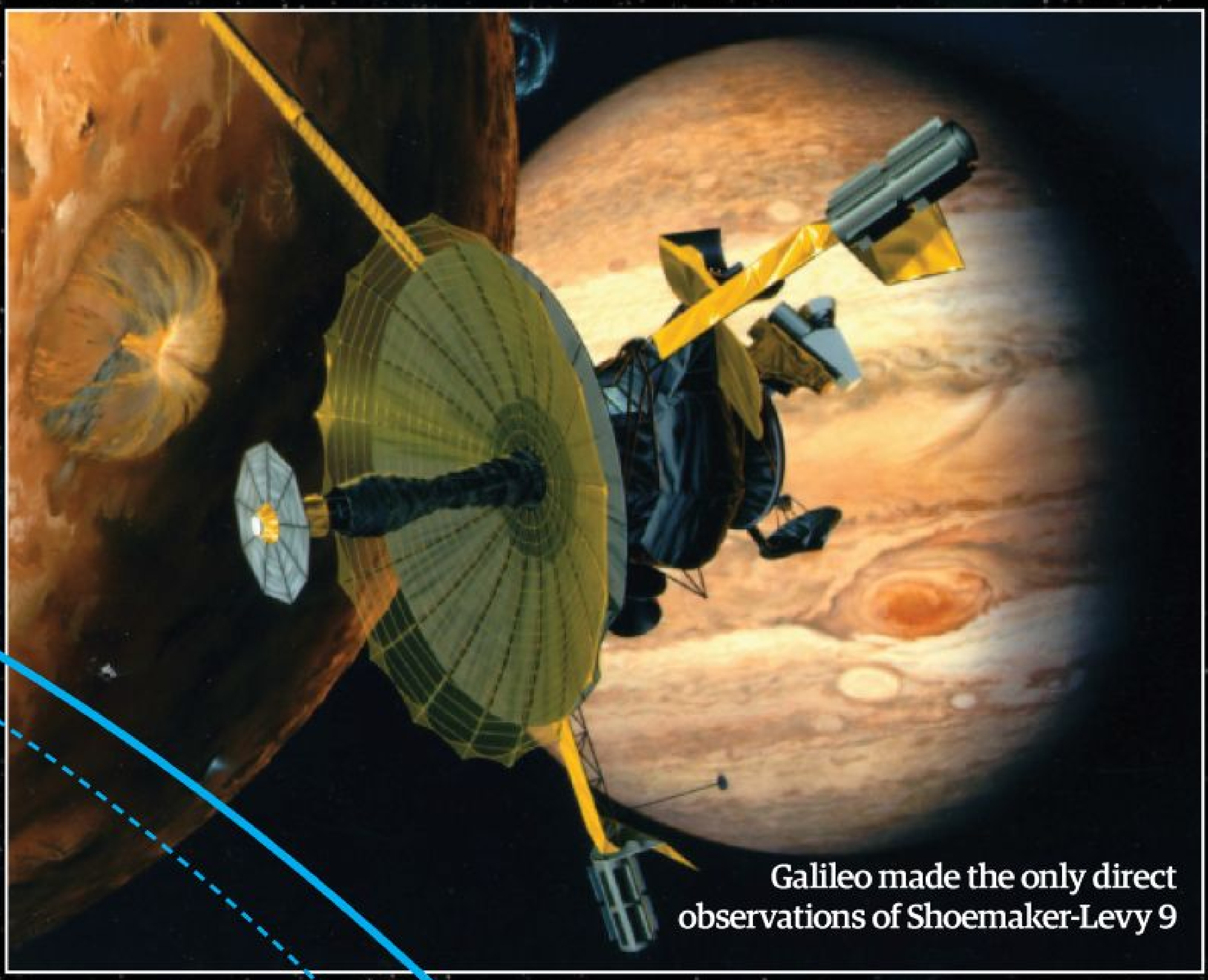
Whatever the role Jupiter currently plays in the Solar System, astronomers will continue to track and observe comets, just like David Levy and Carolyn and Eugene Shoemaker did. Detection for the smaller objects might prove more difficult and in the case of Russia's Chelyabinsk meteorite last year, too late to warn any populated region in its path. Nonetheless, we're learning more and more about these events with every fresh observation, improving our chances of detection in the future and making the world aware that, while Earth is a much smaller target than Jupiter, it's still a viable target in the Solar System's shooting gallery.

Impact Jupiter: sequence of events

Follow the path of Shoemaker-Levy 9 - from its discovery through to its plunge into Jupiter's atmosphere

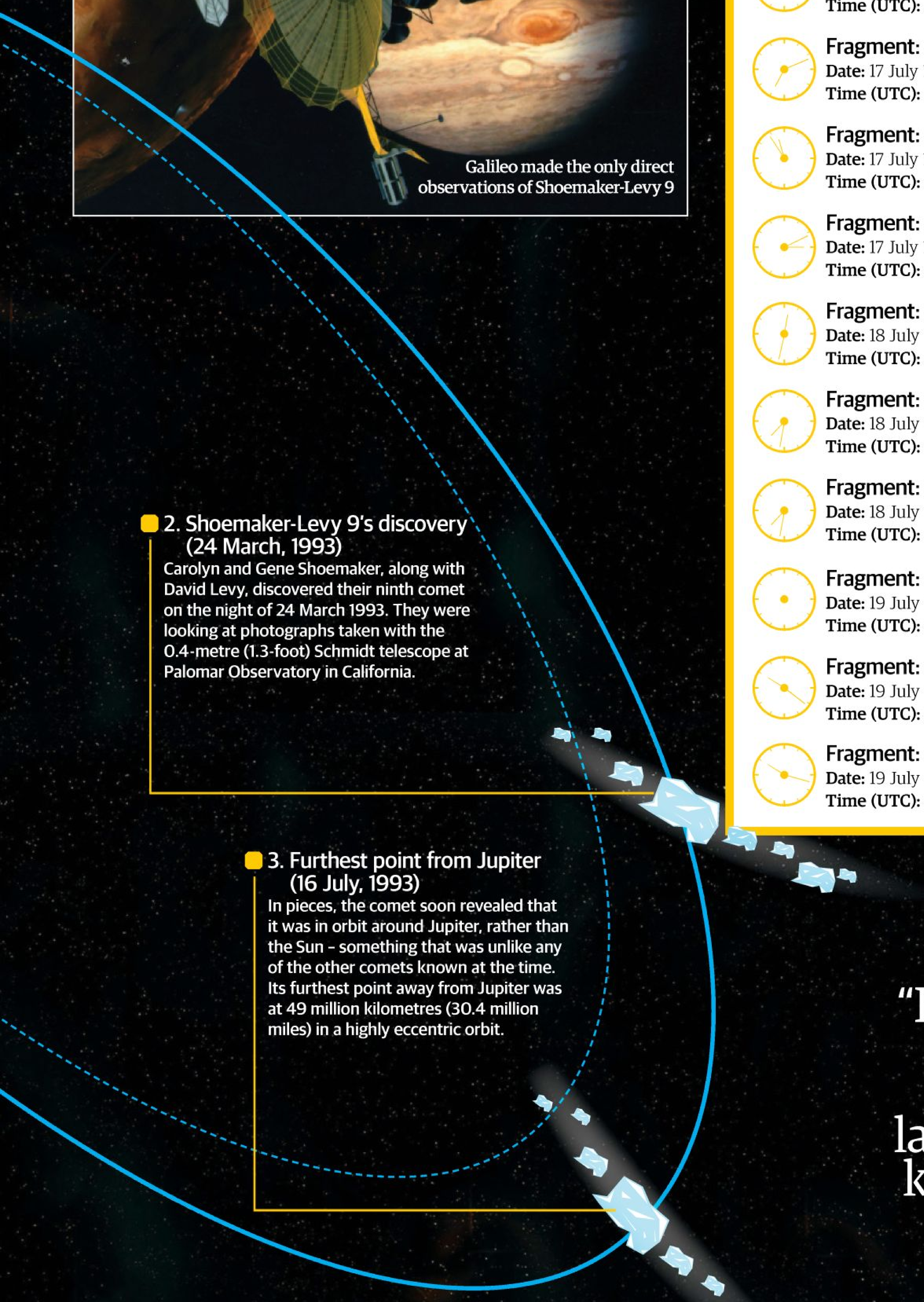


Using the MAGIC infrared camera at the German-Spanish observatory on Calar Alto in Spain, astronomers tracked the impact sites over two months after Shoemaker-Levy 9's fragments smashed into Jupiter


Galileo made the only direct observations of Shoemaker-Levy 9

Shoemaker-Levy 9's fragment impact times

Fragment	Date	Time (UTC)
A	16 July 1994	20:11
B	17 July 1994	02:50
C	17 July 1994	07:12
D	17 July 1994	11:54
E	17 July 1994	15:11
F	18 July 1994	00:33
G	18 July 1994	07:32
H	18 July 1994	19:32
J	19 July 1994	Unknown
K	19 July 1994	10:21
L	19 July 1994	22:17
M	20 July 1994	Unknown
N	20 July 1994	10:31
P2	20 July 1994	15:23
P1	20 July 1994	Unknown
Q2	20 July 1994	19:44
Q1	20 July 1994	20:12
R	21 July 1994	05:33
S	21 July 1994	15:15
T	21 July 1994	18:10
U	21 July 1994	21:55
V	22 July 1994	04:22
W	22 July 1994	08:05



2. Shoemaker-Levy 9's discovery (24 March, 1993)
Carolyn and Gene Shoemaker, along with David Levy, discovered their ninth comet on the night of 24 March 1993. They were looking at photographs taken with the 0.4-metre (1.3-foot) Schmidt telescope at Palomar Observatory in California.

3. Furthest point from Jupiter (16 July, 1993)
In pieces, the comet soon revealed that it was in orbit around Jupiter, rather than the Sun – something that was unlike any of the other comets known at the time. Its furthest point away from Jupiter was at 49 million kilometres (30.4 million miles) in a highly eccentric orbit.

"Fragments punched their way through the planet's upper layer at a speed of 60 kilometres (37 miles) per second"

Hidden planets IN THE SOLAR SYSTEM

How well do we really know our Solar System? Some experts think there are other worlds that could be – or have been – lurking in the shadows, but where are they?

We know that there are other worlds out there far beyond the eight planets of our Solar System, but what if someone told you that there could be celestial objects quite a few light years closer? These are worlds that are hidden away in our very own Solar System – an unacknowledged part of the family that orbits the Sun.

Granted, we seem to have the basic layout of our Solar System pegged. Four terrestrial planets are cut off from the monstrous outer objects by the Asteroid Belt, while even farther away are the icy denizens of the Kuiper Belt. Our neighbourhood is further encased by the Oort Cloud, a spherical form that's chock-a-block with comets. With this in mind, the mere suggestion of hidden planets seems a bit far-fetched. After all, we would surely have found them by now, wouldn't we?

Well, perhaps not, as there's still some odd behaviour in the Solar System that leaves astronomers flummoxed. While some planets may have existed long ago in the past and were lost to some unforgiving force aeons ago, traces of their existence might still remain. Our solar neighbourhood's traumatic past – the so-called Late Heavy Bombardment period – could all be down to the influence of planets that no longer exist. What's happening right now in the Solar System could be down to some world – invisible to us – having fun and games with other objects in the astronomical local vicinity, revealing tantalising clues to its existence in the process.

It was during the 1850s that the first of these elusive planets, later named Vulcan, was thought to have been spotted. The theory of this missing planet was postulated by French mathematician Urbain Le Verrier, who spent much of his time studying the orbit of innermost planet Mercury. He found that, from observation, the planet's orbit differed by around 43 arcseconds every century compared with what was predicted by the classical mechanics of Johannes Kepler and Isaac Newton. The orbit was precessing and Le Verrier thought that some undetected world located between Mercury and the Sun was to blame.

In 1859 Le Verrier received a letter from an amateur astronomer stating that the planet, which seemed to be causing some fuss among many observers, had been found. An amateur, Edmond Lescarbault had been using his four-inch refractor when he noticed a small black dot moving across

the face of the Sun. Having witnessed Mercury move across our star previously in 1845, Lescarbault suspected that what he had witnessed was a new body: the fabled Vulcan.

Satisfied that Lescarbault had detected the inner planet, Le Verrier made an announcement of its discovery in 1860. Other astronomers, unconvinced, questioned the existence of Vulcan but Le Verrier wasn't to be swayed and died in 1877 certain to the end that Vulcan had been found. It wasn't until some time later that general relativity was ultimately able to explain the changes in Mercury's orbit that had originally been attributed to the mystery planet.

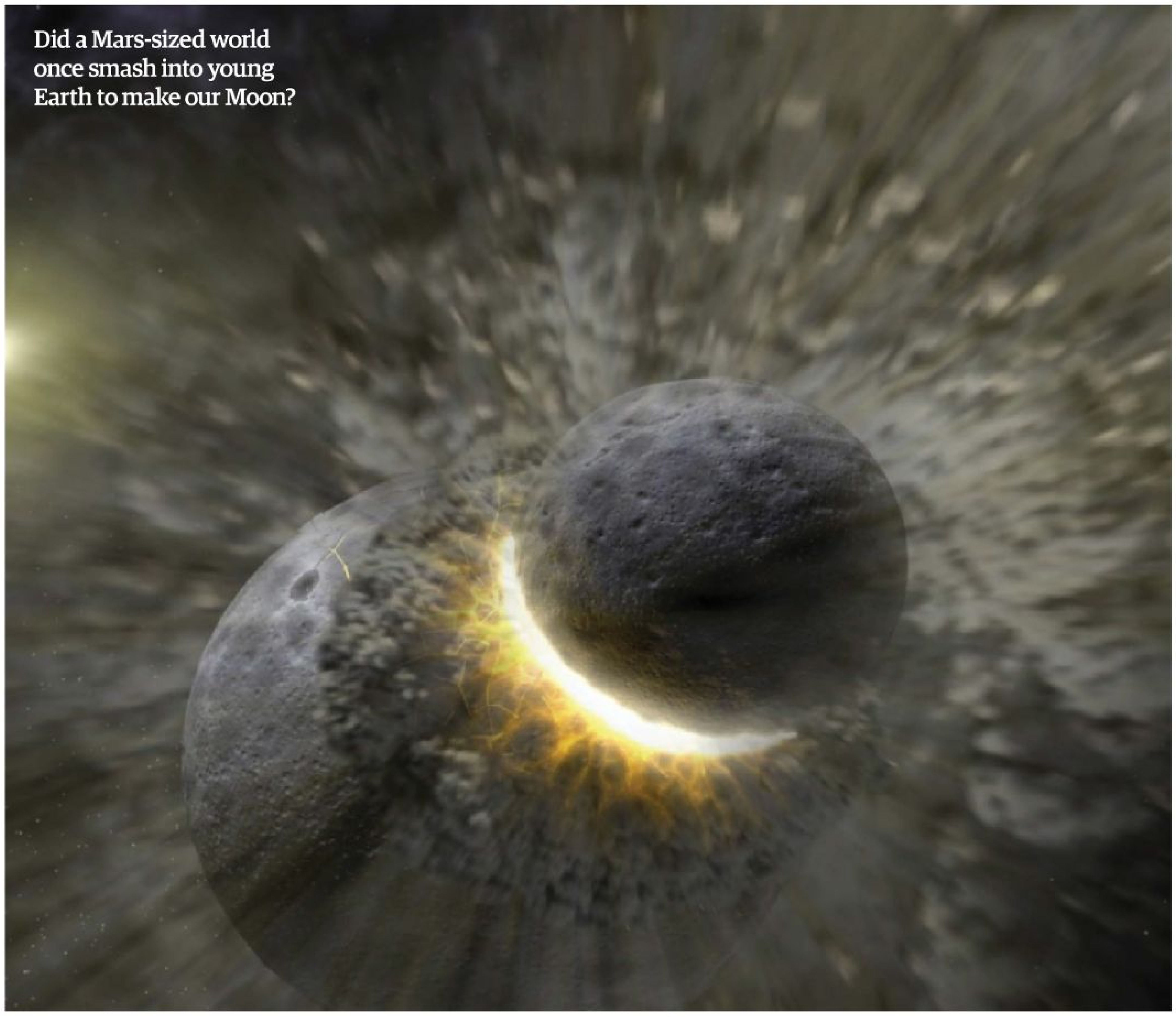
To this day, no planet has been found in Vulcan's position. "It is true that a planet could orbit the Sun closer than Mercury and remain stable," says astronomer John Chambers at the Carnegie Institution's Department of Terrestrial Magnetism. "However, it would have to be at least the size of a large asteroid, otherwise the effect of solar radiation on its orbit would cause it either to collide with Mercury or the Sun within the lifetime of the Solar System. I think observations have ruled out the existence of anything this large."

Yet the hunt still continues – not for a planet called Vulcan, but for much smaller bodies named Vulcanoids, thought to exist between Mercury and the Sun. These would appear in the form of asteroids dancing in a band around our star.

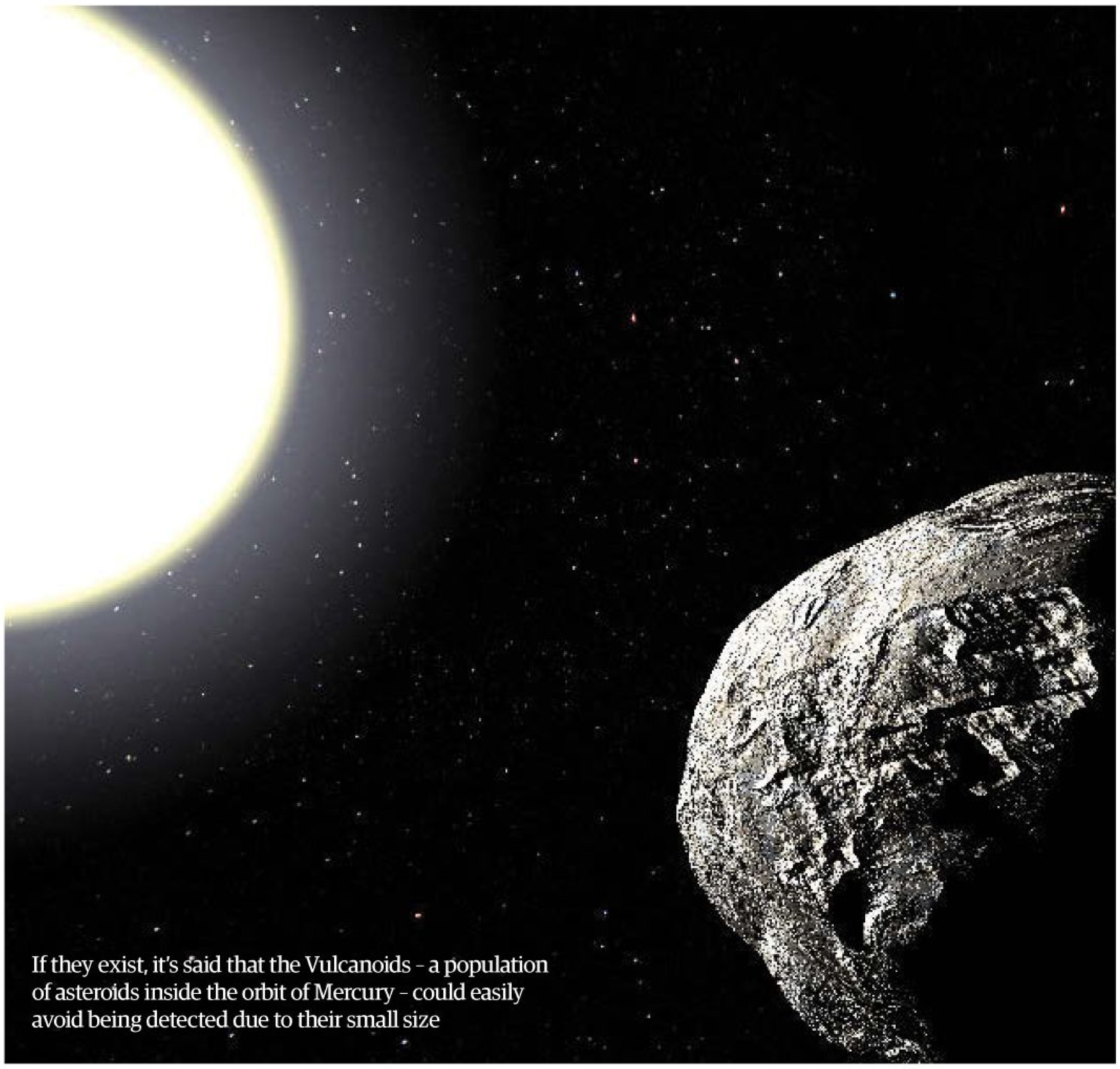
A team hunting for such objects includes Andrew Steffi, Dan Durda and Alan Stern (the principal investigator of the New Horizons mission currently on the way to Pluto), who have searched for Vulcanoids using the help of NASA's STEREO Heliospheric Imager satellites. This trio of spacecraft scrutinises solar eruptions spreading into space. However the satellites have yet to find any sign of Vulcanoids. "By measuring how efficient we were at detecting fake objects, we can say that if there were a Vulcanoid larger than six kilometres (3.7 miles) across, there is a 99.7 per cent chance we would have found it," Steffi explains. "There are low odds of being any Vulcanoid larger than this. Our ability to detect objects smaller than that is limited, for the simple reason that smaller objects reflect less sunlight and therefore appear fainter."

Regardless, there is a small chance that Vulcanoids could still be lurking. While Steffi's team trawled through large amounts of data, David Vokrouhlicky, a professor of astrophysics at Charles University's

> "Vulcanoids could be big enough to remain on stable orbits for 4.5 billion years, but still be too small for us to detect them"
>
> **Andrew Steffi, Vulcanoid hunter**



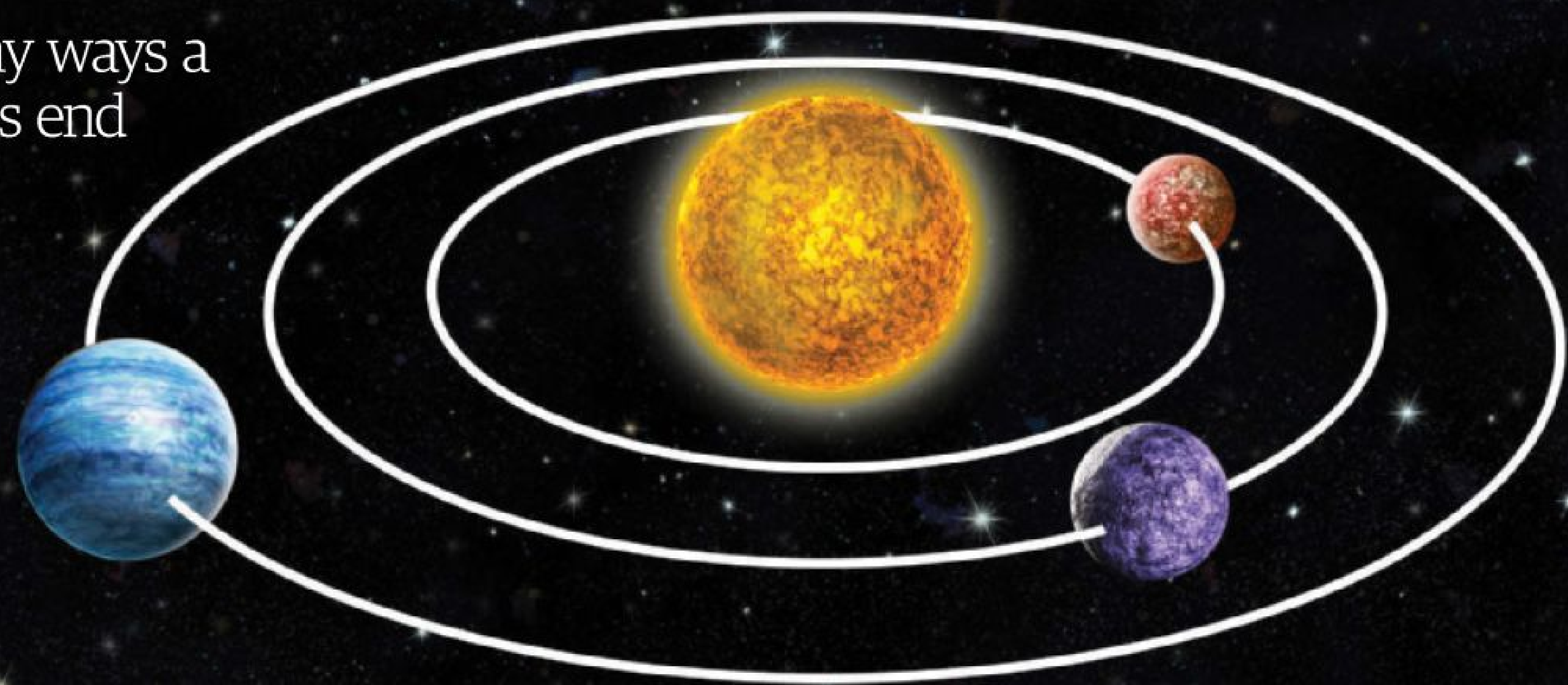
Did a Mars-sized world once smash into young Earth to make our Moon?



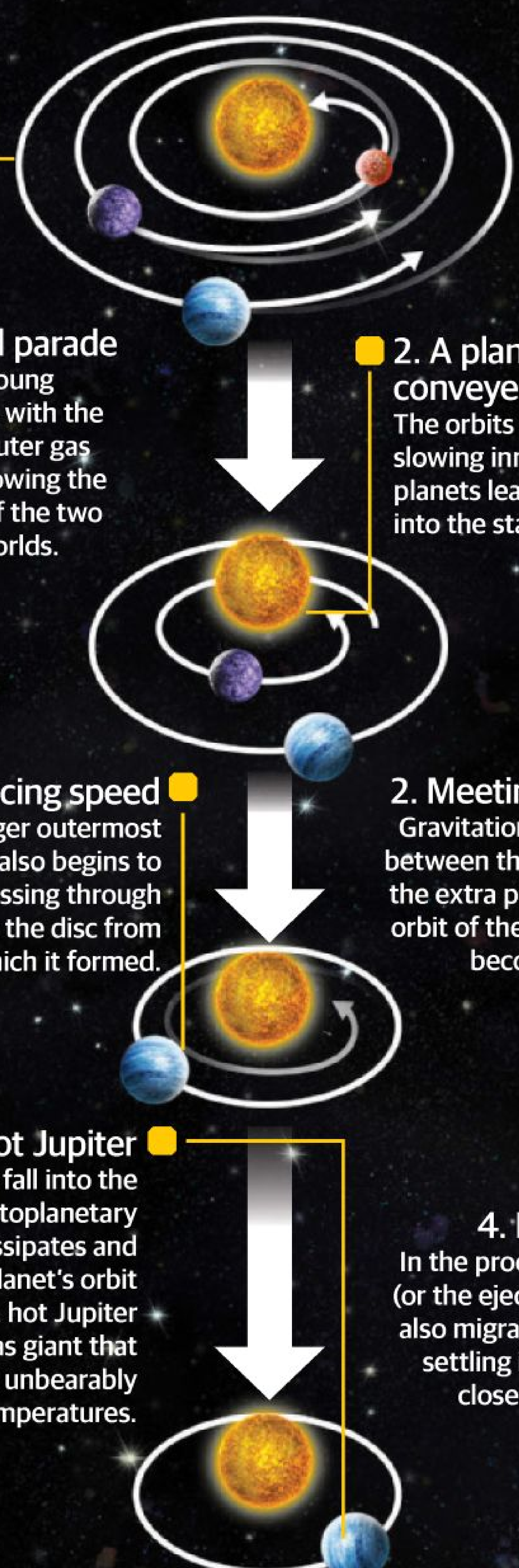
If they exist, it's said that the Vulcanoids – a population of asteroids inside the orbit of Mercury – could easily avoid being detected due to their small size

How planets die

Discover the many ways a world can meet its end



Being eaten alive



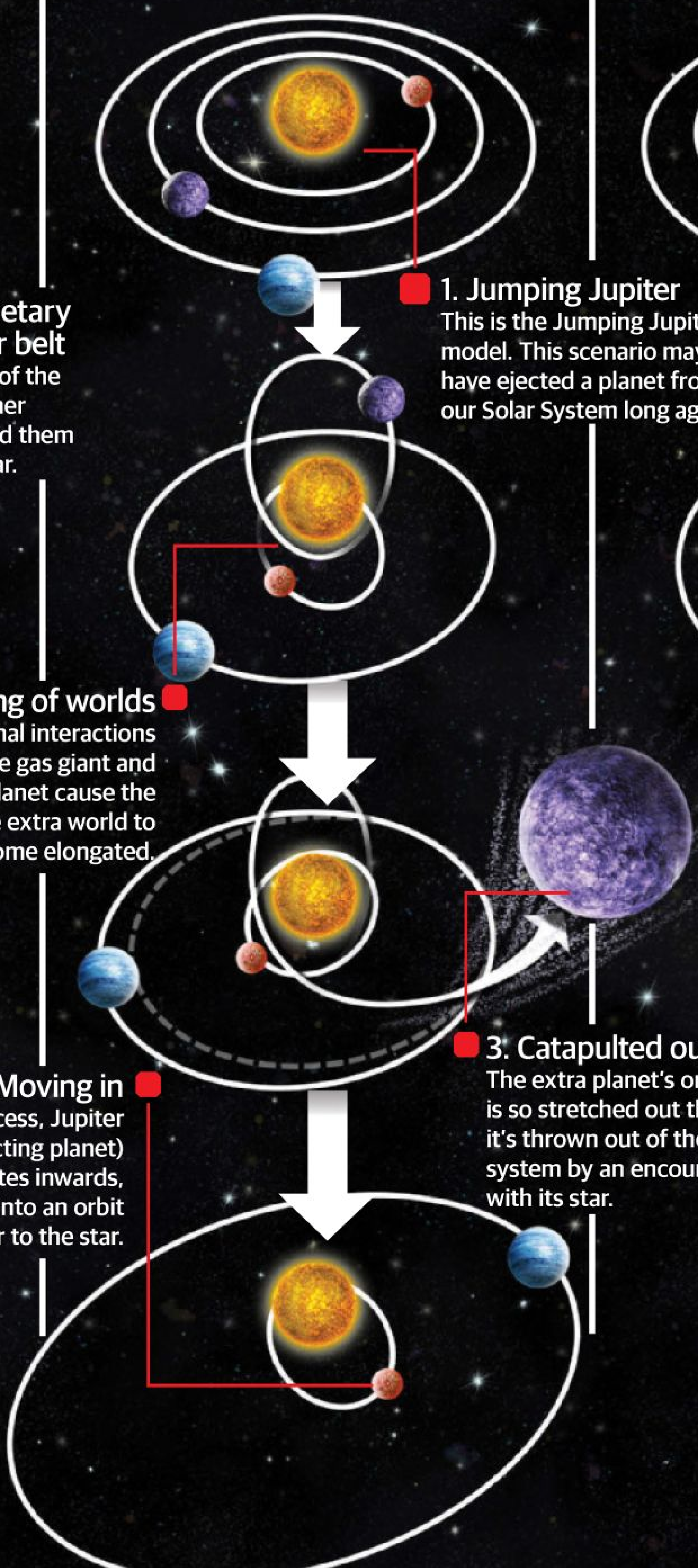
1. Tidal parade
Three young planets, with the larger outer gas giant slowing the orbits of the two inner worlds.

2. A planetary conveyer belt
The orbits of the slowing inner planets lead them into the star.

3. Reducing speed
The larger outermost planet also begins to slow by passing through dust in the disc from which it formed.

4. Hot Jupiter
Before it can fall into the star, the protoplanetary dust disc dissipates and the larger planet's orbit stabilises. A hot Jupiter is born – a gas giant that sizzles at unbearably high temperatures.

Getting kicked out



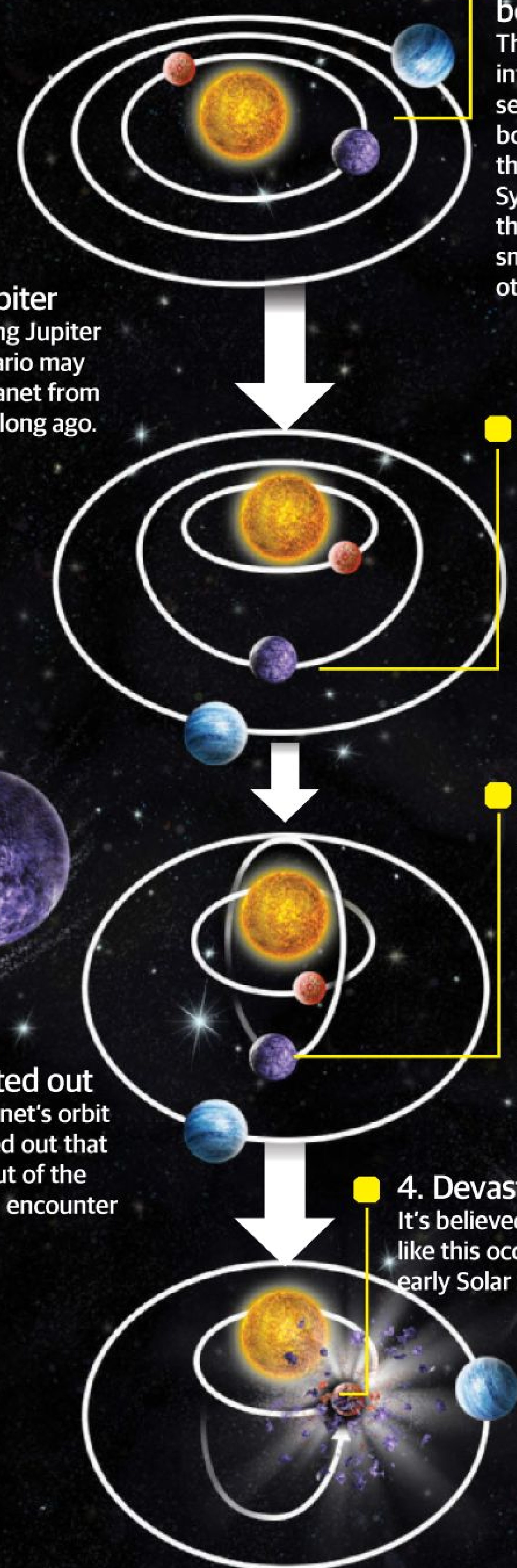
1. Jumping Jupiter
This is the Jumping Jupiter model. This scenario may have ejected a planet from our Solar System long ago.

2. Meeting of worlds
Gravitational interactions between the gas giant and the extra planet cause the orbit of the extra world to become elongated.

3. Catapulted out
The extra planet's orbit is so stretched out that it's thrown out of the system by an encounter with its star.

4. Moving in
In the process, Jupiter (or the ejecting planet) also migrates inwards, settling into an orbit closer to the star.

Collision course



1. In the beginning
The gravitational interactions can send smaller bodies speeding through the Solar System, where they can get into smash-ups with other planets.

2. Pushing out
A resonance between a large planet and a smaller inner planet can amplify and begin to push the inner world out of its orbit.

3. Thrown into chaos
The inner planet is sent into a chaotic path: a highly elongated orbit or a trajectory that will take it out of the planetary system entirely.

4. Devastating impact
It's believed a huge collision like this occurred in the early Solar System.

Astronomical Institute in Prague, has taken a more theoretical approach in the hunt for these chunks of rock on the doorstep of our Sun. "There was some nice work done by Vokrouhlicky and his colleagues, showing that any Vulcanoids smaller than about one kilometre (0.6 miles) would get pushed out of their stable orbits by radiation pressure from the Sun," adds Steffi. "So there is this really narrow window where potential Vulcanoids could be big enough to remain on stable orbits for 4.5 billion years, but still be too small for us to detect them."

That's not to say that Steffi hasn't made some guesses of his own about the Vulcanoids. He and his team think that any potential orbits of these chunks of rock would end up crossing, causing them to smash into one another like bumper cars in a fairground ride. "Since they're so close to the Sun, the relative velocities between two Vulcanoids would be roughly 10-20 kilometres (6.2-12.4 miles) per second and a collision would either break them up or, at least, knock off a bunch of fragments. Each fragment would now be on Vulcanoid-crossing orbits and could hit other members, knocking off more bits," Steffi says. This process, called collisional erosion, can whittle down a population of kilometre-sized or larger objects into smaller pieces in a billion years or less. "It's not too dissimilar to what happened in the movie *Gravity*, where a bunch of high-velocity debris on crossing orbits reduces the larger orbits [of satellites] to fragments."

The Vulcanoids would shrink to such a size that their orbits are modified by the Sun's radiation, directing them on a collision course with Mercury or planetary neighbour Venus, or even throwing them into the fiery heat of the Sun where they would evaporate. With no obvious clues for their existence, Steffi is left feeling somewhat sceptical. "I think it's more likely that Vulcanoids simply don't exist today, if they ever existed at all," he says almost resignedly.

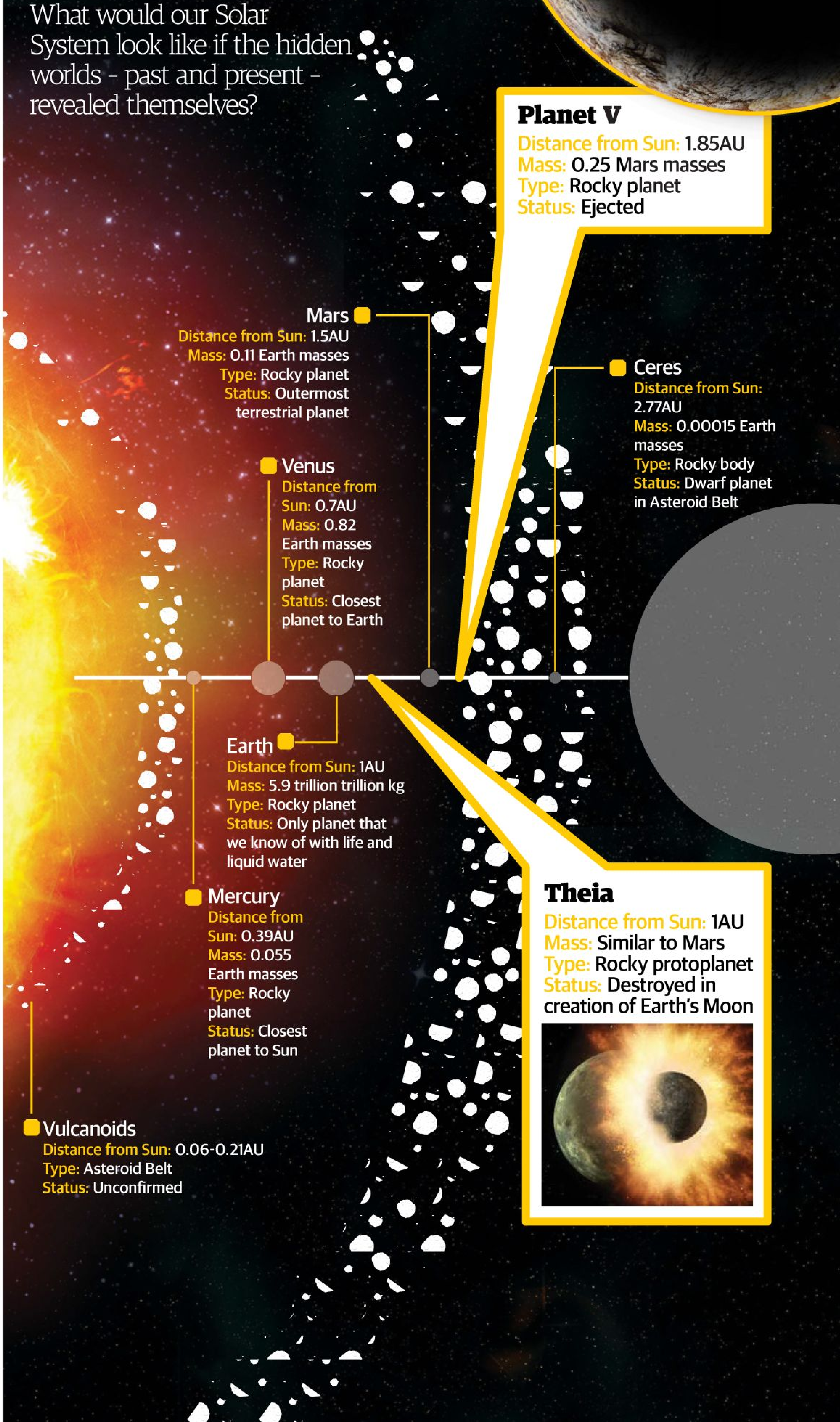
Jack Lissauer, a co-investigator on the exoplanet mission Kepler at NASA's Ames Research Center, is a bit more hopeful. He thinks that the Vulcanoids are very likely to have been part and parcel of the younger Solar System. "Some tiny Vulcanoids that formed from the burnt-out remains of comets may even exist today," he says.

When it comes to speculating about other worlds that could be or could have been knocking around our neighbourhood, Lissauer likes to stay quite open-minded. After all, alongside the SETI Institute's Mark Showalter, he discovered two of Uranus' moons: Mab and Cupid. What's more, he thinks that a fifth terrestrial world similar to our inner planets could once have orbited between Mars and the Asteroid Belt, created with the other terrestrial planets during the planet-forming era. This additional world, he reasoned, could explain the Late Heavy Bombardment (LHB) when a huge shower of asteroids wreaked havoc during Earth's Hadean period – our planet's first geologic eon.

This was a hellish period in Earth's past, when it was rife with unbearable heat and intense volcanic activity, beginning with its formation some 4.5 billion years ago. "The LHB is an event in the history of the Solar System responsible for most of the craters and impact basins we see today on the Moon, Mars and Mercury," explains Chambers, who is also in favour

The invisible Solar System

What would our Solar System look like if the hidden worlds – past and present – revealed themselves?



Makemake
Distance from Sun: 45.8AU
Mass: Unknown
Type: Dwarf planet
Status: Icy body in Kuiper Belt

Haumea
Distance from Sun: 43AU
Mass: 0.00066 Earth masses
Type: Dwarf planet
Status: Icy body in Kuiper Belt

Suspected super Earth or ice giant
Distance from Sun: 100s of AU
Mass: Up to 10 Earth masses
Type: Unknown
Status: Undetected

Jupiter
Distance from Sun: 5.2AU
Mass: 317.8 Earth masses
Type: Gas giant
Status: Largest planet in Solar System

Saturn
Distance from Sun: 9.6AU
Mass: 95.2 Earth masses
Type: Gas giant
Status: Sixth planet from the Sun

Eris
Distance from Sun: 68AU
Mass: 0.0028 Earth masses
Type: Dwarf planet
Status: Icy trans-Neptunian object

Pluto
Distance from Sun: 39AU
Mass: 0.00218 Earth masses
Type: Dwarf planet
Status: Former planet

Uranus
Distance from Sun: 19.2AU
Mass: 14.5 Earth masses
Type: Ice giant
Status: Tipped onto its side following suspected collision

2012 VP113
Distance from Sun: 80-100s of AU
Mass: Unknown
Type: Dwarf planet
Status: Icy trans-Neptunian object

Neptune
Distance from Sun: 30AU
Mass: 17 Earth masses
Type: Ice giant
Status: Last known planet in Solar System

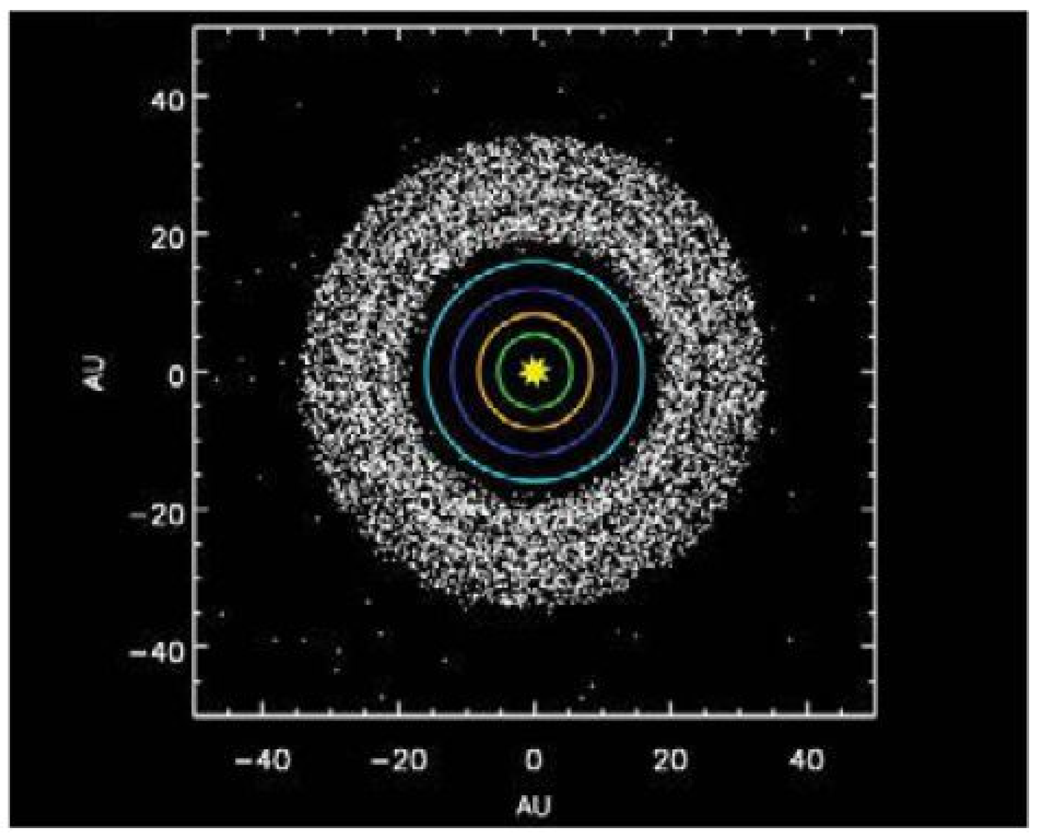
Third ice giant
Distance from Sun: Approximately 15AU
Mass: Around Uranus' mass
Type: Ice giant
Status: Ejected

Tyche/Planet X
Distance from Sun: 15,000AU
Mass: Up to 2 Jupiter masses
Type: Gas giant
Status: Undetected

Nemesis
Distance from Sun: 95,000AU
Mass: 0.0075-0.5 times mass of Sun
Type: Brown dwarf or red dwarf
Status: Undetected

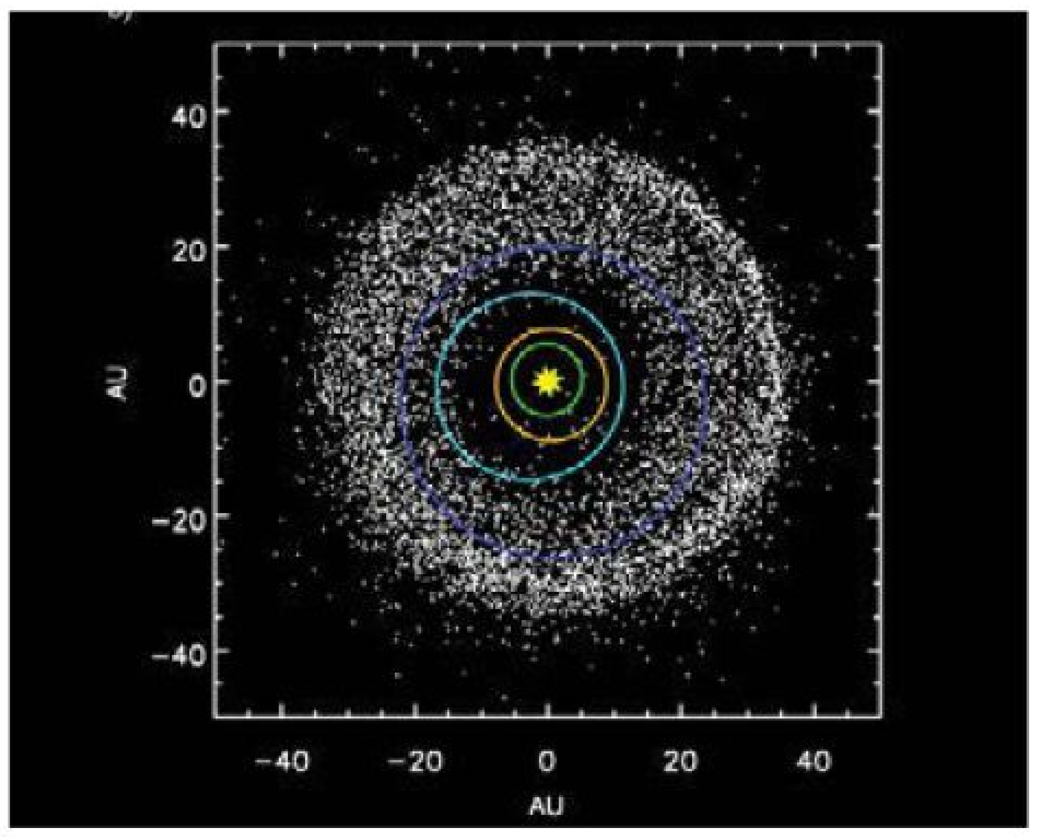
The Nice model

Named after the city where it was initially developed, the Nice model describes what we understand to be the dynamic evolution of our Solar System. The theory states that the giant planets broke free from an initially compact configuration into their current positions.



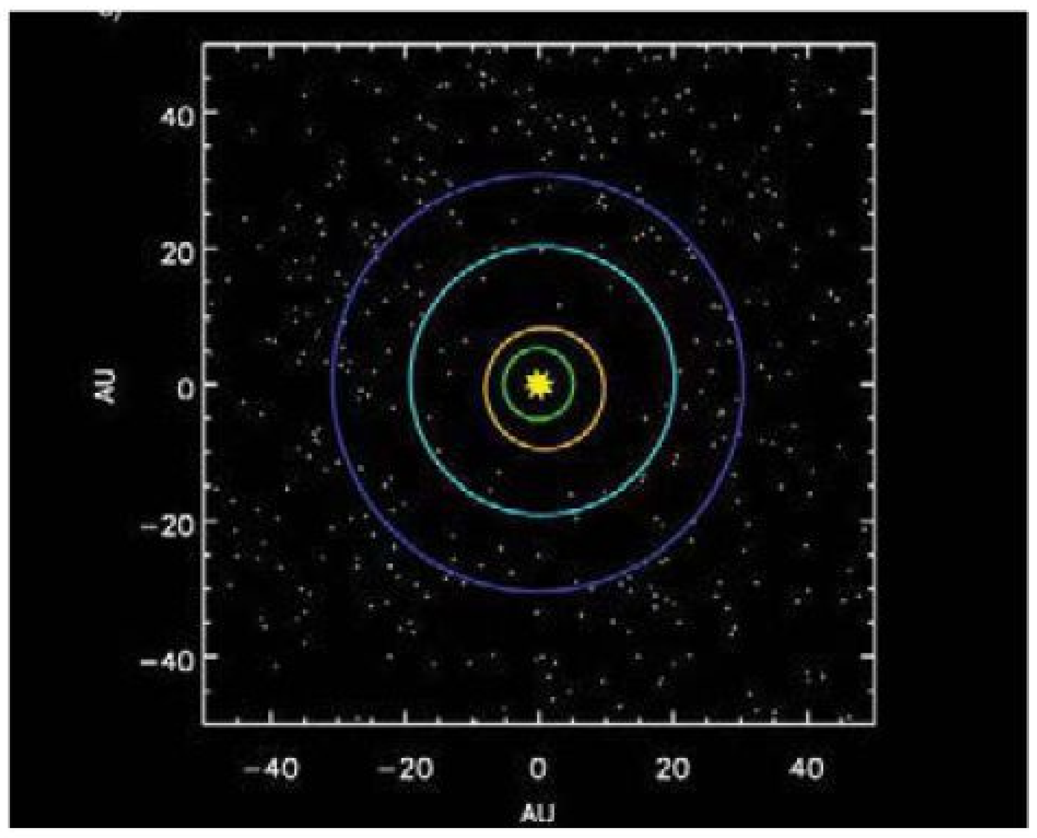
Young planetary orbits

After the dissipation of the gas and dust of the Solar System's primordial disc, Jupiter, Saturn, Uranus and Neptune could be found on a nearly circular orbit somewhere between 5.5 and 17AU.



Causing complete chaos

After a slow migration, Jupiter and Saturn cause a regular and periodic gravitational influence on each other, causing eccentric orbits, which destabilises the Solar System entirely.



A shower of planetesimals

Neptune and Uranus hit the planetesimal, scattering rocks from their orbits to the outer reaches, removing nearly all the primordial disc's mass that batters the inner planets.

The Nice theory suggests the migration of giant planets, where their orbits are altered and they move closer to their stars

"After Earth formed, a protoplanet called Theia smashed into our planet, ripping off a large chunk of our world's mantle"

of the idea of a Planet V. Alongside Lissauer, he came up with the idea of this extra planet. "The mystery of the LHB is that it happened about half a billion years after the planets finished forming, so something must have changed in the Solar System at that time in order to cause all those impacts."

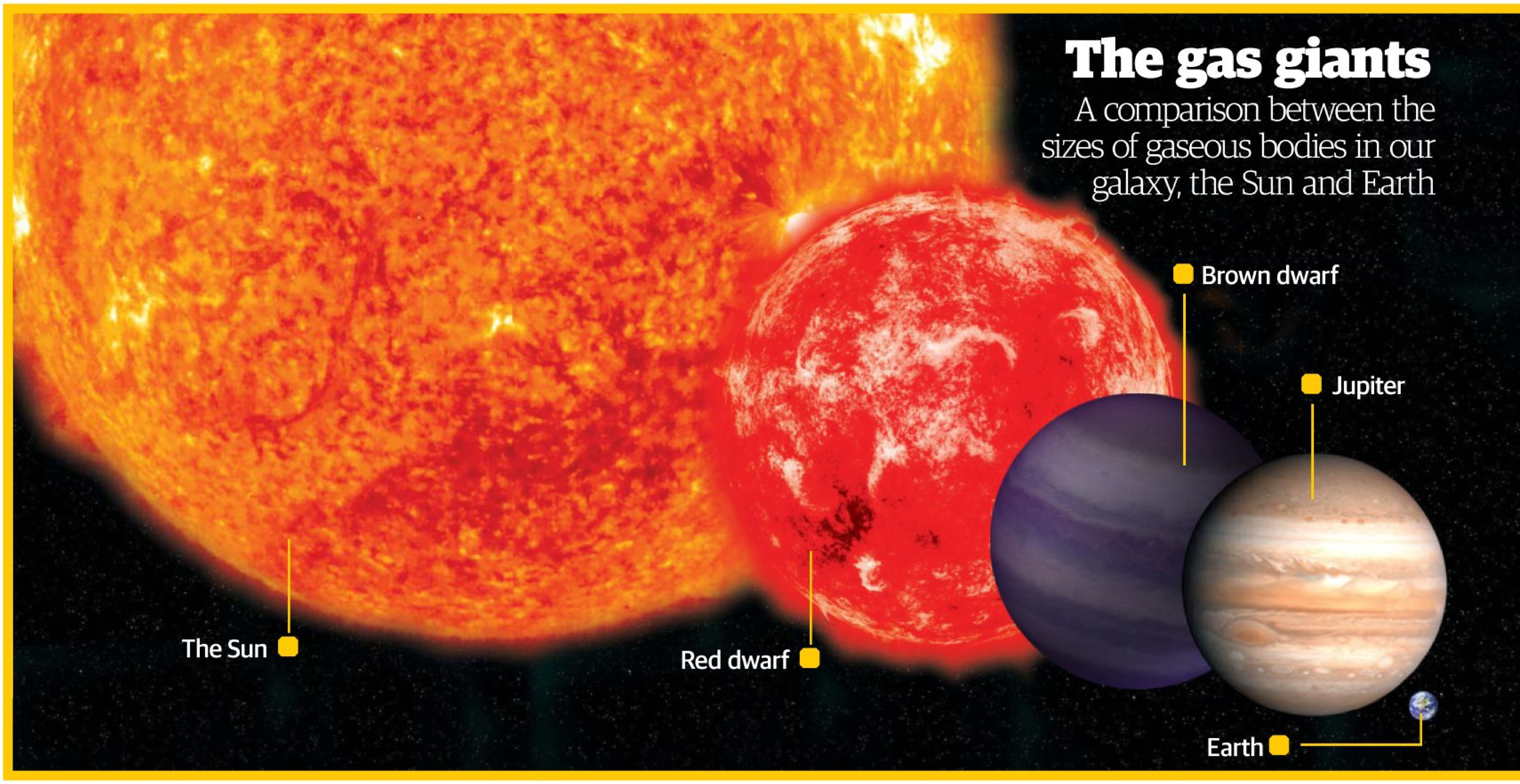
Both Chambers and Lissauer warn that the idea of a Planet V is highly speculative and for now remains unproven. However, Chambers relates a story to **All About Space** that chronicles this past world's possible life in our Solar System. "An extra planet located between Mars and the Asteroid Belt could remain there for hundreds of millions of years before its orbit became unstable and it either fell into the Sun or was thrown out by Jupiter's gravity," he says. "For the final portion of its lifetime, this extra planet would have had an orbit crossing the Asteroid Belt and its gravity may have nudged many asteroids out of the belt onto orbits. Here they eventually collided with the Moon or one of the planets, creating the LHB."

The large number of craters that pepper the rocky worlds of our Solar System are still being probed by astronomers across the entire scientific community. Another idea for the so-called LHB brought forward by an independent group of researchers who met at Nice Observatory, in France, is aptly named the Nice model. In this scenario the orbits of the younger outer planets altered slowly over time as the gravity of the gas giants steadily removed many asteroids from the Kuiper Belt out beyond the orbit of Neptune. "Shortly before the time of the LHB, the orbits of Jupiter and Saturn entered a temporarily unstable configuration called a resonance. Probably Jupiter was orbiting the Sun exactly three times for every two orbits of Saturn," says Chambers of the Nice model. "For a few million years the orbits of Jupiter, Saturn, Uranus and Neptune changed dramatically and their gravity flung asteroids out of both the Asteroid and Kuiper Belts, some of which hit the Moon and inner planets."

Of course, at present, we're not fully sure of which theory – the Nice model or that of Chambers and Lissauer – is correct. While it hasn't escaped the notice of Chambers that both could be wrong, he states that many researchers seem to favour the Nice model. Either way, there seems to be a general consensus that chunks of space rock have somehow been thrown wildly across the Solar System, crashing into anything and everything in their path – leaving their legacy for astronomers to find.

Fortunately for Chambers and Lissauer, academics like Alessandro Morbidelli (among those who originally suggested the Nice model) and Ramon Brasser have been giving Planet V's existence some careful thought. The duo calculated that for Planet V to create the force of the LHB it would need to have cast out a good 95 per cent of the Asteroid Belt during this era in the Solar System – or a whopping 98 per cent of the inner portion of this same belt.

Running computer simulation after computer simulation, the astronomers could see that Planet V would have been ejected some 400 million years after the formation of the Solar System and would have had a mass of around a quarter of Mars. "I



The Nice Observatory's 76cm (30in) refractor, when built, boasted the title of the world's largest and longest telescope

Hidden planet hunter

Data from NASA's Wide-field Infrared Survey Explorer (WISE), now known as NEOWISE, turned up no evidence for Nemesis or Planet X in its observations

think they are basically right," Chambers admits. "It's almost certainly true that the Asteroid Belt once contained much more mass than it does today."

Looking around our Solar System, you'll find that the current total mass of asteroids is tiny, at around two-thousandths that of Earth's. "Models for the formation of the Solar System all agree there was a lot more stuff there when the planets began forming," Chambers says. "There are numerous ideas for how the Asteroid Belt lost most of its original material – mostly these ideas involve Jupiter throwing its weight around in one way or another, so that its gravity removed objects from the Asteroid Belt." In the light of these theoretical models, the idea that the Asteroid Belt lost a lot of material due to the existence of a so-called Planet V isn't a huge stretch of the imagination.

There is a variation on the Planet V hypothesis, which proposes that it was another ice giant, such as Neptune, nestled quite comfortably between ringed planets Saturn and Uranus. "This planet could have orbited between Saturn and Uranus, while Neptune could have orbited closer to the Sun than Uranus prior to the LHB," speculates Lissauer. This fifth giant planet is likely to have been thrown to its doom by being catapulted out of the Solar System following a gravitational encounter with neighbouring Saturn and Jupiter, in the so-called Jumping Jupiter scenario. Here Jupiter jumps due to gravitational interactions with Uranus or Neptune, before throwing out another planet (a fifth world) that's been left out in the cold.

The Southwest Research Institute's David Nesvorny thinks that the jumbling of planets could have scattered many small bodies, pushing some inwards and others outwards, with some ending up in the Kuiper Belt. Others are likely to have smashed into the terrestrial planets and the Moon. "Researchers have simulated the orbital evolution of hypothetical objects between the orbits of the outer planets using computers. In most cases these orbits are so unstable that the objects are removed in less than a billion years," says Chambers. "I believe one study found a slim chance that something could survive between Saturn and Uranus for the age of the Solar System, but it would have to be no more than a few hundred kilometres in diameter, otherwise it would have been seen by now."

The impacts of comets during the LHB are separate events to one of the biggest collisions of all that's thought to have created our Moon. Scientists believe that shortly after Earth formed, a protoplanet called Theia smashed into our planet, ripping off a large chunk of our world's mantle, which went into forming the Moon. Theia, which was around the size of Mars, was totally destroyed. The early Solar System was swarming with bodies like Theia, some of which crashed into planets like this young world did, while others were ejected into the Oort Cloud or beyond.

While an extra planet may hold the answer to the LHB, comets continue to periodically impact the inner planets. One astronomer in particular thought there was an unusual regularity to this deadly influx of space snowballs, revealed in the period between mass extinctions on Earth, when it was implied these collisions wiped out many species on our planet. In 1984 American professor of physics Richard Muller

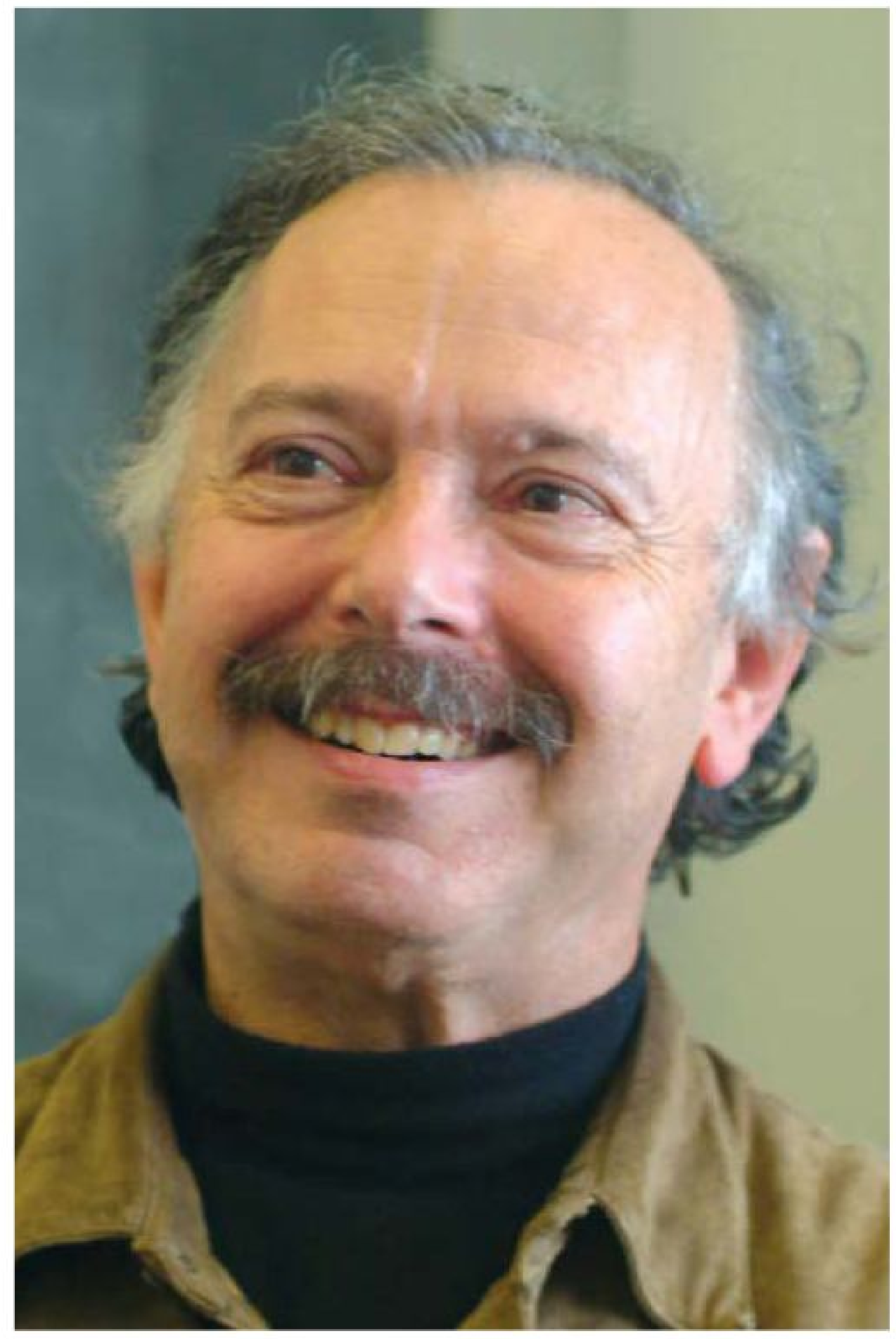
suggested that a companion to the Sun – either a brown or red dwarf called Nemesis – lurked beyond the comet-packed Oort Cloud at a distance of around 1.5 light years. This body perturbed the comets in the Oort Cloud as it orbited every 26 million years, causing a wave of comets to come crashing through the Solar System. Looking back at geological records, Muller believed that Nemesis would explain a cycle of mass extinctions, snuffing out swathes of life on our planet, which seems to occur at regular intervals – roughly every 26 million years.

Several research teams agree there is no denying the pattern here. However, just what form Nemesis takes isn't agreed by all parties. David Whitmire and Albert Jackson believe that Nemesis is a failed star – a brown dwarf that stalks the outer edges of the Solar System. Muller, on the other hand, argues that this object is likely to be a red dwarf star, glowing at an apparent magnitude of somewhere between 7 and 12 from our position on Earth. "Red dwarfs are far more common," Muller explains. "I suspect [Whitmire and Jackson] mistakenly believed that a red dwarf would have been seen and so were forced to assume a far fainter brown dwarf."

Either way, Nemesis would shine brightly in infrared light. WISE – NASA's Wide-field Infrared Survey Explorer – carefully scanned the sky searching for, among other things, a companion star to the Sun, but the mission's reels of data have turned up nothing. Scientists have now ruled out any Jupiter-sized planets out to 26,000 times the distance of Earth from the Sun and any Saturn-sized bodies out to 10,000 times that distance in the Oort Cloud. Even Muller accepts it isn't looking good for the hypothetical stellar companion. "Maybe it isn't there," he says. "I think the WISE measurements were pretty thorough… Calculations show that Nemesis must be orbiting in the plane of the galaxy, otherwise its orbit would be unstable. I don't know if WISE was able to do a thorough job in the plane of the galaxy, so it could be hiding there."

The results from WISE also pose similar problems for a theory suggested by a group led by John Matese, who proposed the presence of a gas giant in the Oort Cloud to explain the similarities between the points of origin of long-period comets. They called this unseen planet Tyche, but you might have heard it being referred to as 'Planet X'.

"WISE's observations have indeed ruled out the possibility of a planet at the large mass end of the range that we suggested was possible," explains Matese, claiming there is a loophole that could still allow Tyche to exist. "It's not clear that WISE can rule out the existence of a planet at the low mass end, around one or two times the mass of Jupiter, at the distances suggested. I admit that most of the possible scenarios that we allowed for have been precluded."



Richard Muller suggested that our Sun has a companion red dwarf star called Nemesis which has caused mass extinctions on our planet every 26 million years

"It's not clear that WISE can rule out the existance of a planet at the low mass end, around one or two times the mass of Jupiter"

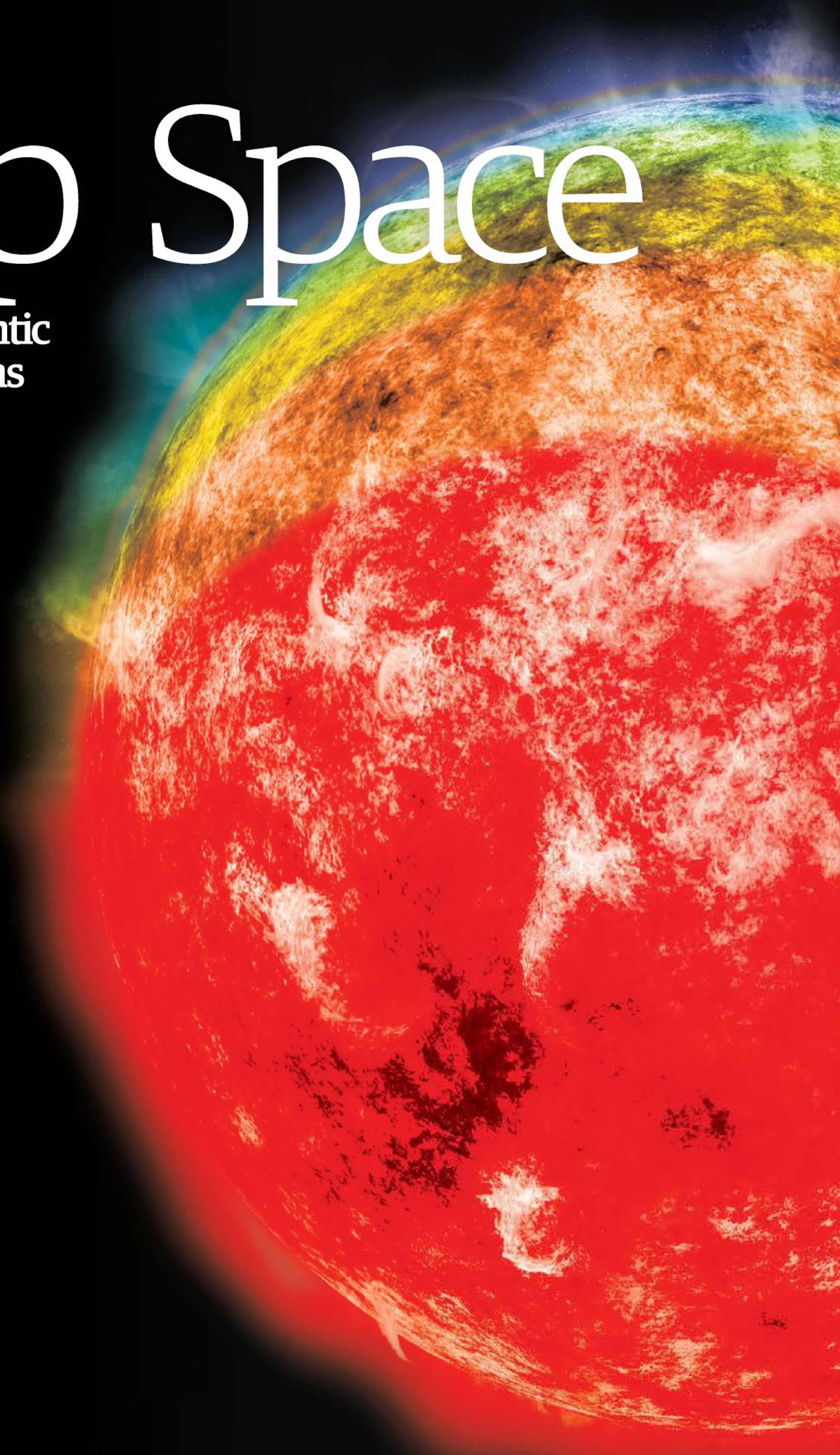
So, both Muller and Matese hold out only slim hope for their respective unseen objects, but if Nemesis and Tyche don't exist, it doesn't mean that the Oort Cloud and Kuiper Belt are empty of large objects. Four dwarf planets – Pluto, Eris, Makemake and Haumea – are known to exist out there and now a fifth dwarf in the outer Solar System has been found, currently referred to as 2012 VP113.

This new world, found by the Dark Energy Camera (DECam) on the NOAO four-metre (13-foot) telescope in Chile, is the most distant object uncovered so far, reaching hundreds of times farther from the Sun than Earth. According to its discoverers, Scott Sheppard of Carnegie Institution and Chad Trujillo of Gemini Observatory, the similarity of its orbit to other distant world residents of the Kuiper Belt and inner Oort Cloud suggest that something is pushing these bodies into these orbits. That something could be a lost world up to ten times the mass of Earth – another hidden planet for scientists to unmask.

Many astronomers predict that dozens or even hundreds of planets could be found at the far end of the Solar System, in the chilly expanse of the Oort Cloud. Some may be ejected there by interactions with other bodies, while others may have been flung so far out, having wandered so many light years in distance, that they've been captured by another star as an exoplanet. With high-tech observatories scanning inside and outside our Solar System, it might only be a matter of time before what was once a hidden planet reveals itself as an additional member of our Solar System ●

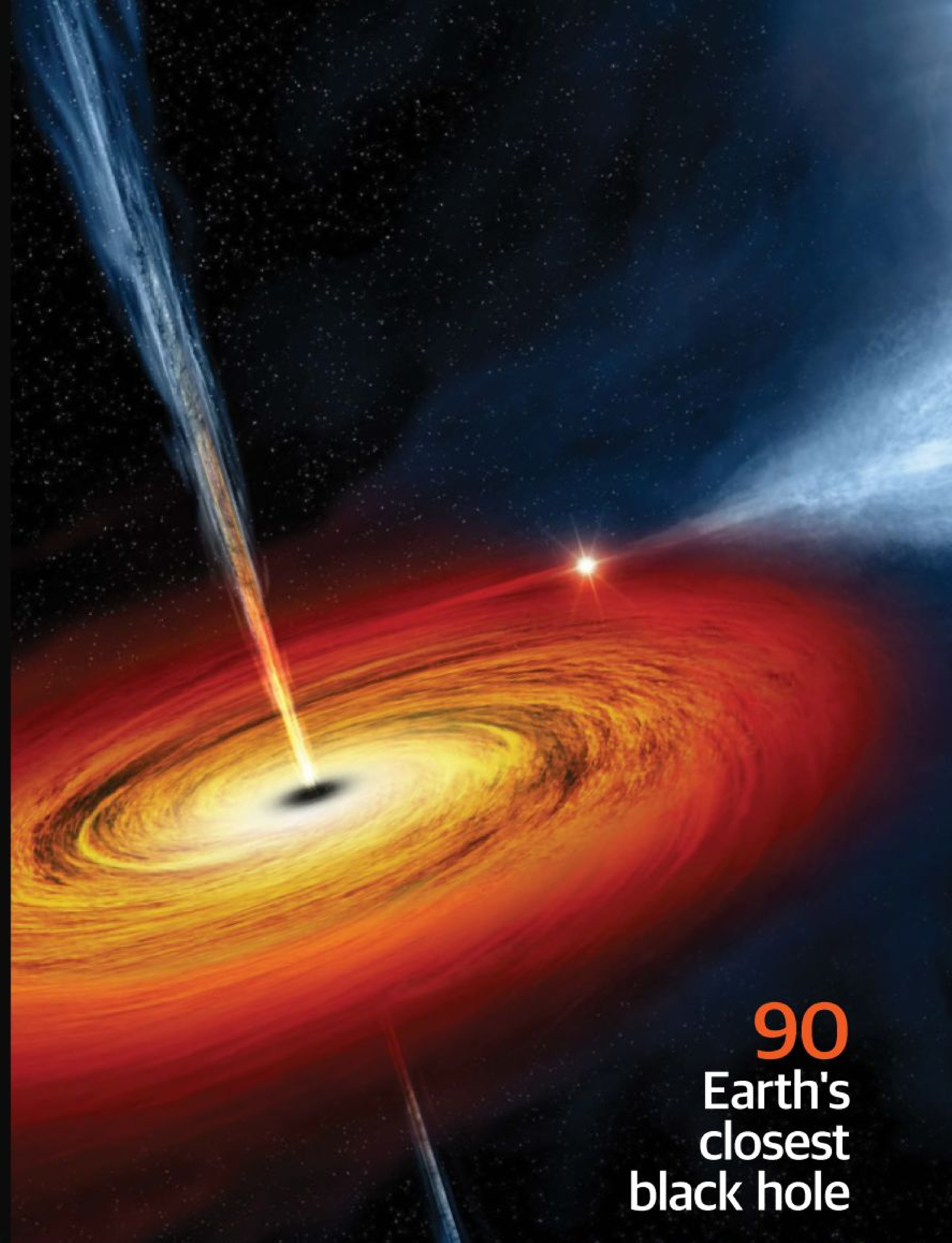
Deep Space

Mammoth stars, gigantic black holes and trillions of new worlds



"Their lifetimes can run into hundreds of billions, even trillions of years"

110
Red dwarfs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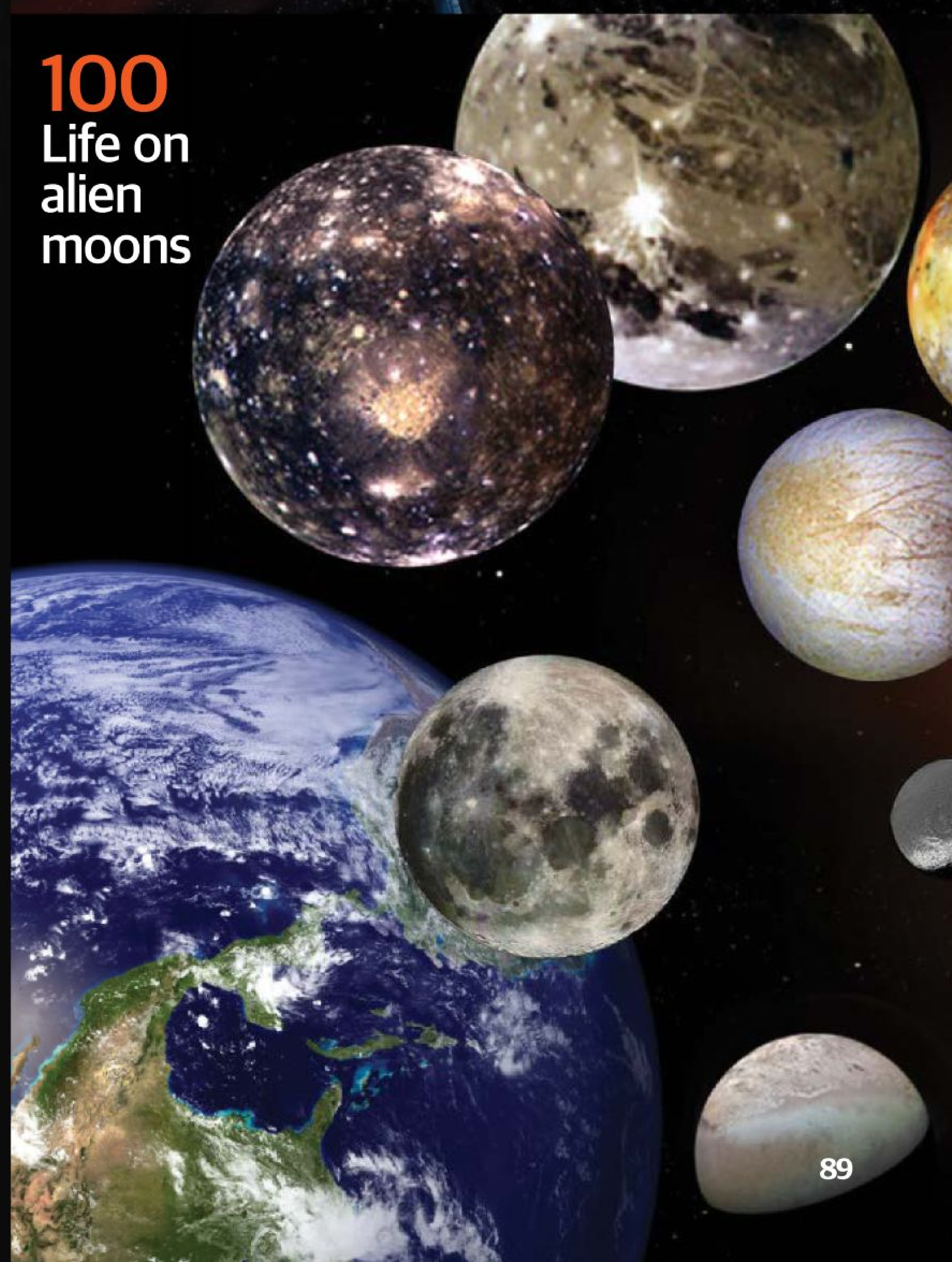
Earth's closest black hole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Life on alien moons

All About... EARTH'S CLOSEST BLACK HOLE

Embedded in a rich stream of the Milky Way some 6,070 light years from Earth, Cygnus X-1 is a strange binary star containing the nearest known black hole to Earth

The distinctive constellation of Cygnus, the Swan, is one of the most famous in the sky. It includes the famous Northern Cross asterism and flies south along one of the brightest and nearest parts of the Milky Way, parallel to the Cygnus Rift created by a dust cloud 300 light years from Earth. The brightest star, Deneb, is usually taken to mark the swan's tail, while the beautiful double star called Albireo, marks its beak. Fairly obvious wings extend to either side of the swan's body, while another bright star, Eta (h) Cygni, lies in the middle of the swan's neck.

Long-exposure photographs reveal a host of faint objects invisible to the naked eye. Not just stars, there are also clouds of interstellar gas such as the North America nebula NGC 7000 (a star-forming region close to Deneb) and the Veil nebula - the remnant of an ancient supernova explosion in the swan's south-western wing. Invisible radiation wavelengths reveal even more detail - radio telescopes show the full extent of the Cygnus Loop (of which the Veil nebula is a part) and Cygnus A - a pair of huge radio-emitting jets surrounding a distant galaxy. High-energy X-rays uncover the constellation's strangest and best-known object - the black hole Cygnus X-1.

One of the brightest X-ray sources in the entire sky, Cygnus X-1 was discovered in the mid-1960s as a result of an early experiment in space-based astronomy. When Aerobee sounding rockets were launched in 1964 to carry detectors on high-suborbital flights above the atmosphere, they detected eight strong radiation sources from different parts of the sky. Most of them seemed to coincide with distant bright galaxies, but one X-ray source - less than half a degree away from Eta Cygni in the swan's neck - seemed to have no such association.

In 1970 NASA launched the first dedicated X-ray astronomy satellite, Uhuru, with Cygnus X-1 as a priority for further study. Extended observations showed its X-ray output seemed to be fluctuating several times a second, suggesting it must be coming from a relatively small region, perhaps about the diameter of Saturn.

X-rays are notoriously hard to pin down, however, and the precise location of Cygnus X-1 remained elusive. It was only in 1971, when radio astronomers found that Cygnus X-1 was also a radio source, that astronomers got their first clue to the mystery. At first its radiation seemed to be coming from a distant blue supergiant star, catalogued HD 226868. However, within a few months astronomers Louise Webster and Paul Murdin of the Royal Greenwich Observatory, as well as Charles Thomas Bolton of the University of Toronto, independently discovered changes in the visible star's spectrum, indicating it moves back and forth every few days. This suggests that it forms a binary system, locked in an orbital waltz with an unseen object of considerable mass that was otherwise completely invisible.

Black holes (so dense that light cannot escape their gravity) had been theorised as early as the 1780s, but the physics underlying such bizarre objects (and a possible process for their formation) weren't described until the 1930s. Before then, they remained an intriguing object for cosmologists and theoretical physicists, but looking at their measurements of Cygnus X-1, astronomers realised they might be observing a black hole for the first time.

Cygnus constellation

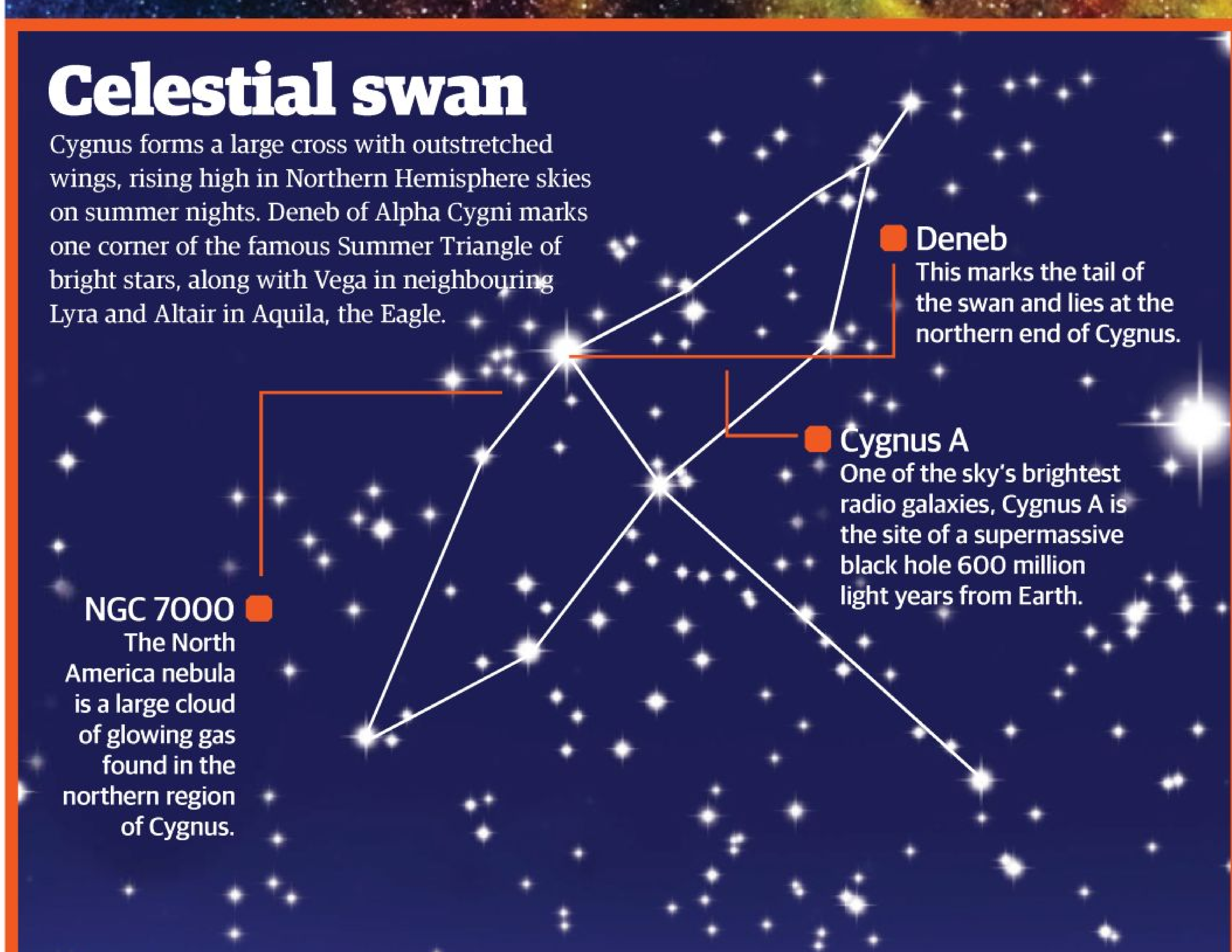
The Tulip nebula, Sharpless 101, is just one of the beautiful but faint objects visible in this night-sky wonder

NGC 6871
This small star cluster consists of about 50 newborn blue and white stars.

X-ray view
In an image from NASA's Chandra satellite, X-ray emissions from the hot disc around the Cygnus X-1 black hole are dominant, while the companion star HD 226868 disappears.

Celestial swan

Cygnus forms a large cross with outstretched wings, rising high in Northern Hemisphere skies on summer nights. Deneb of Alpha Cygni marks one corner of the famous Summer Triangle of bright stars, along with Vega in neighbouring Lyra and Altair in Aquila, the Eagle.

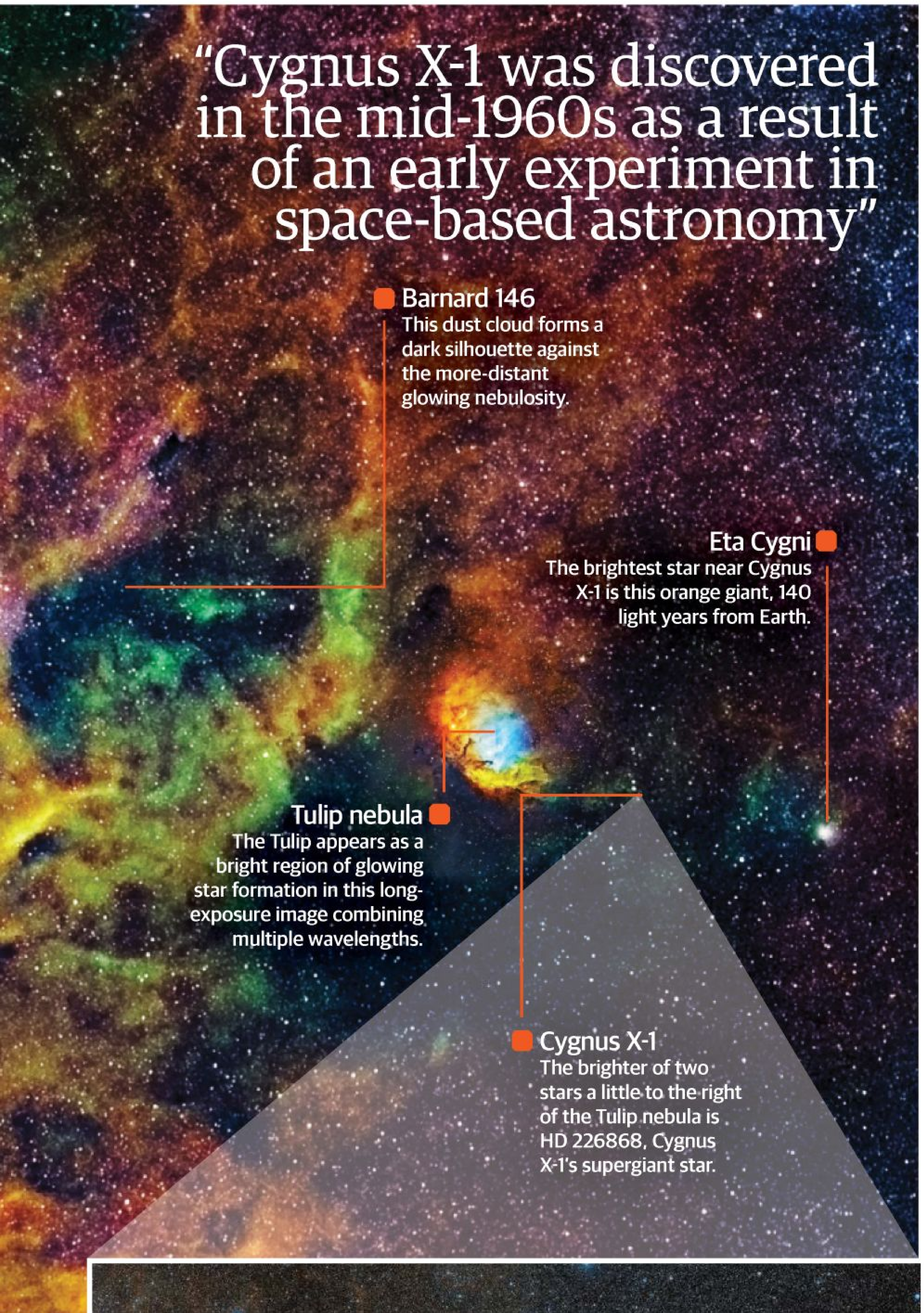


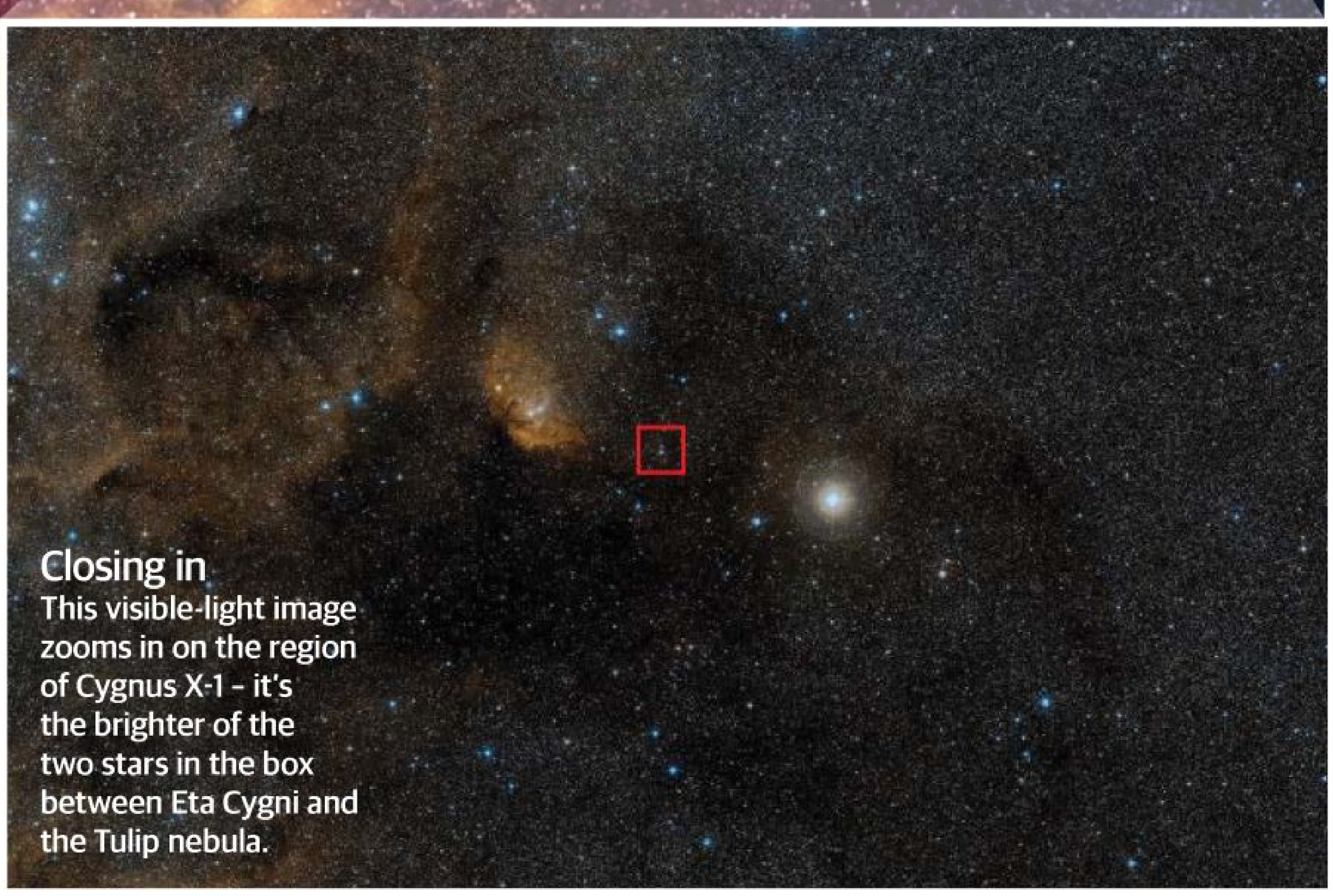
Deneb
This marks the tail of the swan and lies at the northern end of Cygnus.

Cygnus A
One of the sky's brightest radio galaxies, Cygnus A is the site of a supermassive black hole 600 million light years from Earth.

NGC 7000
The North America nebula is a large cloud of glowing gas found in the northern region of Cygnus.

> "Cygnus X-1 was discovered in the mid-1960s as a result of an early experiment in space-based astronomy"




Closing in
This visible-light image zooms in on the region of Cygnus X-1 – it's the brighter of the two stars in the box between Eta Cygni and the Tulip nebula.

Cygnus X-1 by numbers

The nearest black hole to Earth is an extreme object in many ways

6,070 ly

Cygnus X-1's distance from Earth according to the most-accurate radio measurements.

5.6 days

The period in which the two components of Cygnus X-1 orbit each other.

14.8 Suns

The mass of the Cygnus X-1 black hole, according to the latest research.

0.2 AU

Approximate distance between the black hole and its companion star - 20 per cent of the Earth-Sun distance.

800 times per second

The black hole's rotation period.

26 km

The black hole's Schwarzschild radius – the size of its event horizon or point of no return.

350,000 Suns

Approximate luminosity of the black hole's companion star.

30,000 km

Estimated diameter of the super-hot accretion disc around the Cygnus X-1 black hole.

Inside Cygnus X-1

How this binary system has been tearing itself apart in one of the most volatile stellar partnerships

Cygnus X-1's black hole is thought to be the remnant of a massive star that died in a supernova a few million years ago. This brilliant stellar explosion left behind a core so dense and massive that it collapsed beyond the point where any internal pressure could hold it up.

A tiny, impossibly dense point in space known as a singularity was formed, the gravity of which is so great that not even light can escape it. The singularity seals itself off from the external universe within a barrier called an event horizon, marking the last point from which light can overcome its gravity. It's the event horizon that forms the boundary of a black hole as we see it from the external universe – the more massive the singularity, the more powerful its gravity and the larger its event horizon.

So how does this object, that's barely visible, produce the powerful X-rays that make Cygnus X-1 stand out so much? The answer lies in its relationship with its companion star, HD 226868. This stellar monster, with a mass measured to be between 20 and 40 times that of the Sun, pumps out up to 400,000 times as much energy. As the radiation forces its way out from the star's core it causes the outer layers to swell up to 17 times the solar diameter, heating the surface to a searing blue-hot 31,000 degrees Celsius (56,000 degrees Fahrenheit).

> "As the radiation forces its way out from the star's core, it causes the outer layers to swell up to 17 times the solar diameter, heating the surface to a searing blue-hot 31,000 degrees"

HD 226868 is classed as a blue supergiant, but like all stars of its kind, it's losing mass rapidly – the high temperatures at its surface cause its outer layers to boil away into space, creating a powerful stellar wind. HD 226868 is thought to shed an entire Sun's worth of material every 400,000 years.

Based on the speed at which the two objects circle one another, astronomers estimate the black hole has a mass of about 14.8 Suns and orbits at only twice the visible star's radius. This is far enough away for the orbit to remain stable, but close enough for the black hole's gravity to distort its companion's shape into something like that of a teardrop. As the star spins on its axis with respect to Earth, we see different amounts of its surface and so its brightness appears to vary slightly.

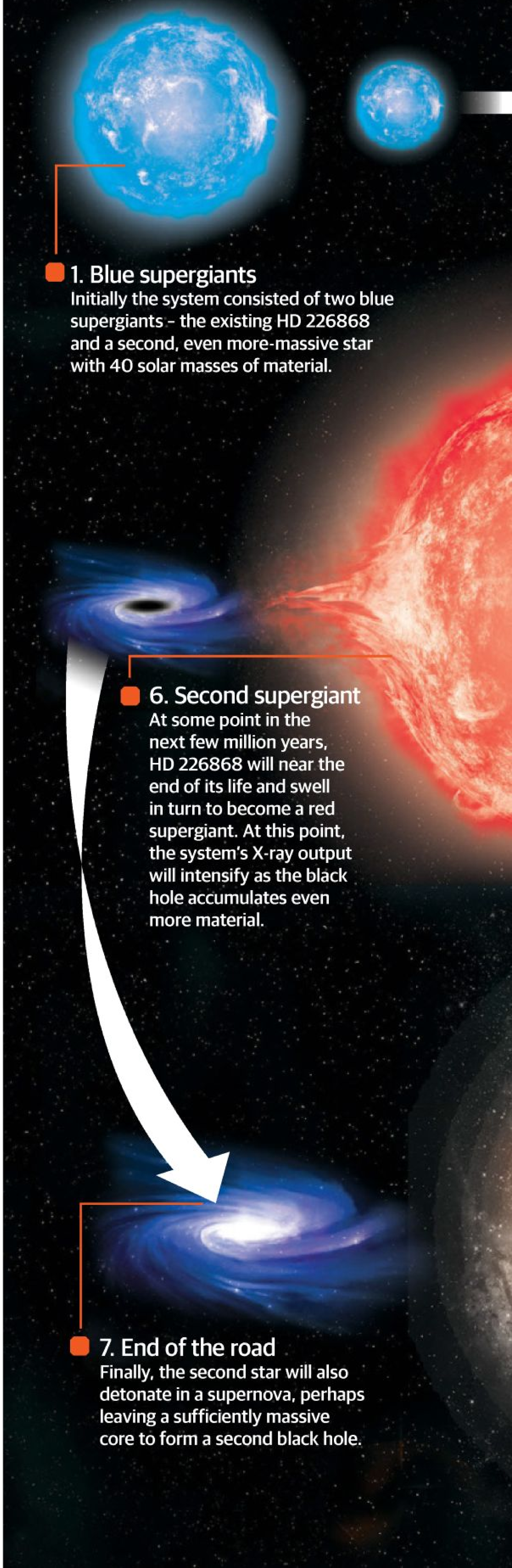
The black hole's gravity isn't quite strong enough to pull material completely away from the star's outer layers (as happens in some other binary systems), but particles ejected into HD 226868's stellar wind are rapidly pulled towards the black hole on a spiral path. The falling material creates a flattened disc around the black hole and friction between gases moving at different speeds in various parts of the disc heats them to very high temperatures.

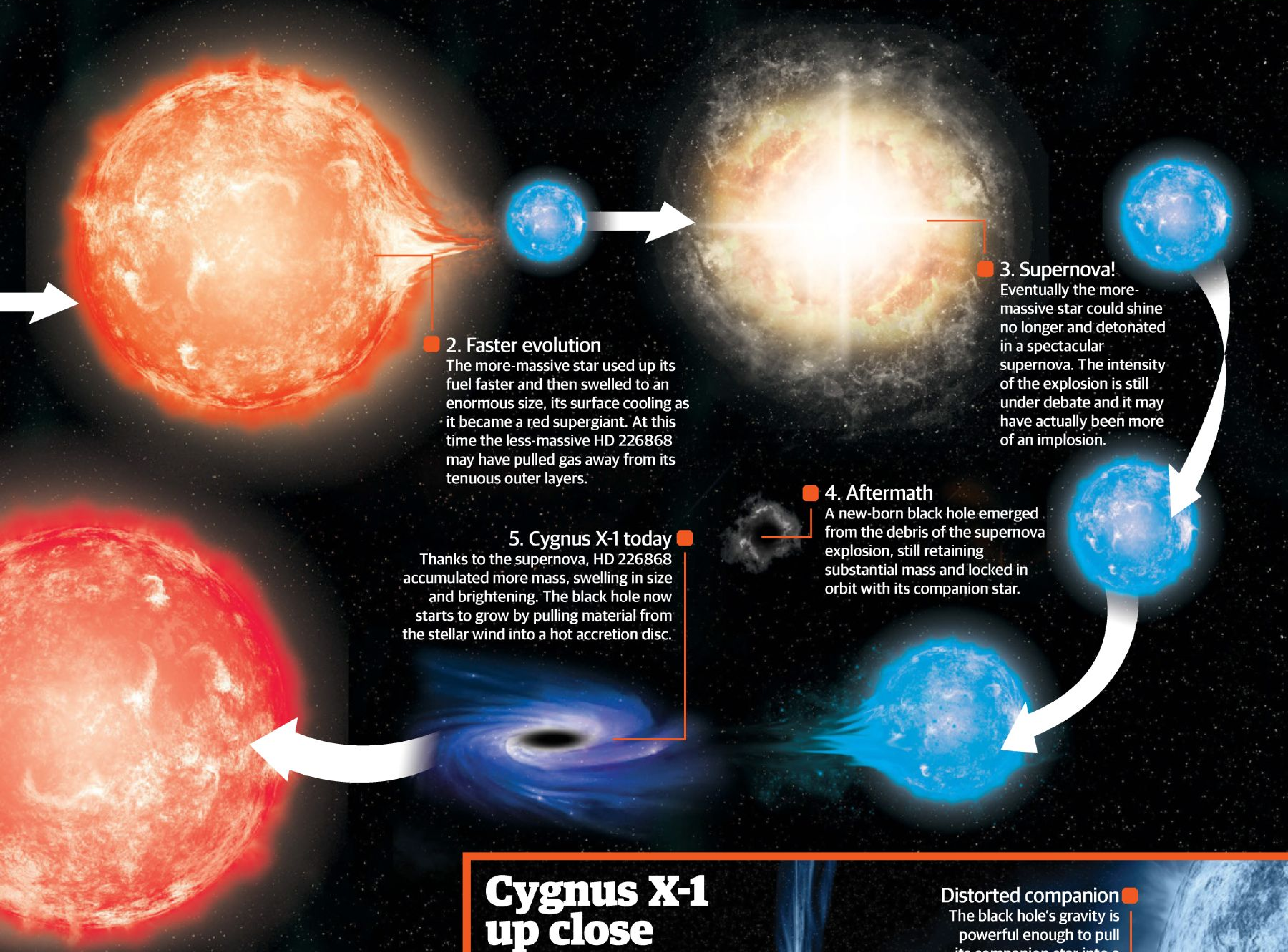
The innermost regions break down into an electrically charged gaseous plasma at more than 10 million degrees Celsius (18 million degrees Fahrenheit), emitting relatively long-wavelength, soft X-rays. These rays then gain additional energy through a process called Compton scattering, which involves individual photons of radiation interacting with electron particles moving at high speeds within a transparent corona above and below the thick disc. Ultimately this boosts the emitted photons to the hard X-ray part of the spectrum, giving Cygnus X-1 an effective temperature of more than a billion degrees.

Cygnus X-1's X-ray output flickers on a timescale of milliseconds as the amount of gas being fed into the central black hole varies. The output also goes through periodic dips with cycles of 5.6 days and 300 days. These dips seem to be caused by the X-ray disc's partial disappearance behind an intervening doughnut of gas around the supergiant, but the system also displays other patterns that aren't understood. In particular the corona that produces its hard X-rays sometimes disappears, leaving only the more-variable soft X-ray emission behind for scientists to eventually uncover.

Evolving system

This sequence shows key stages in the past and future development of the unique Cygnus X-1 system





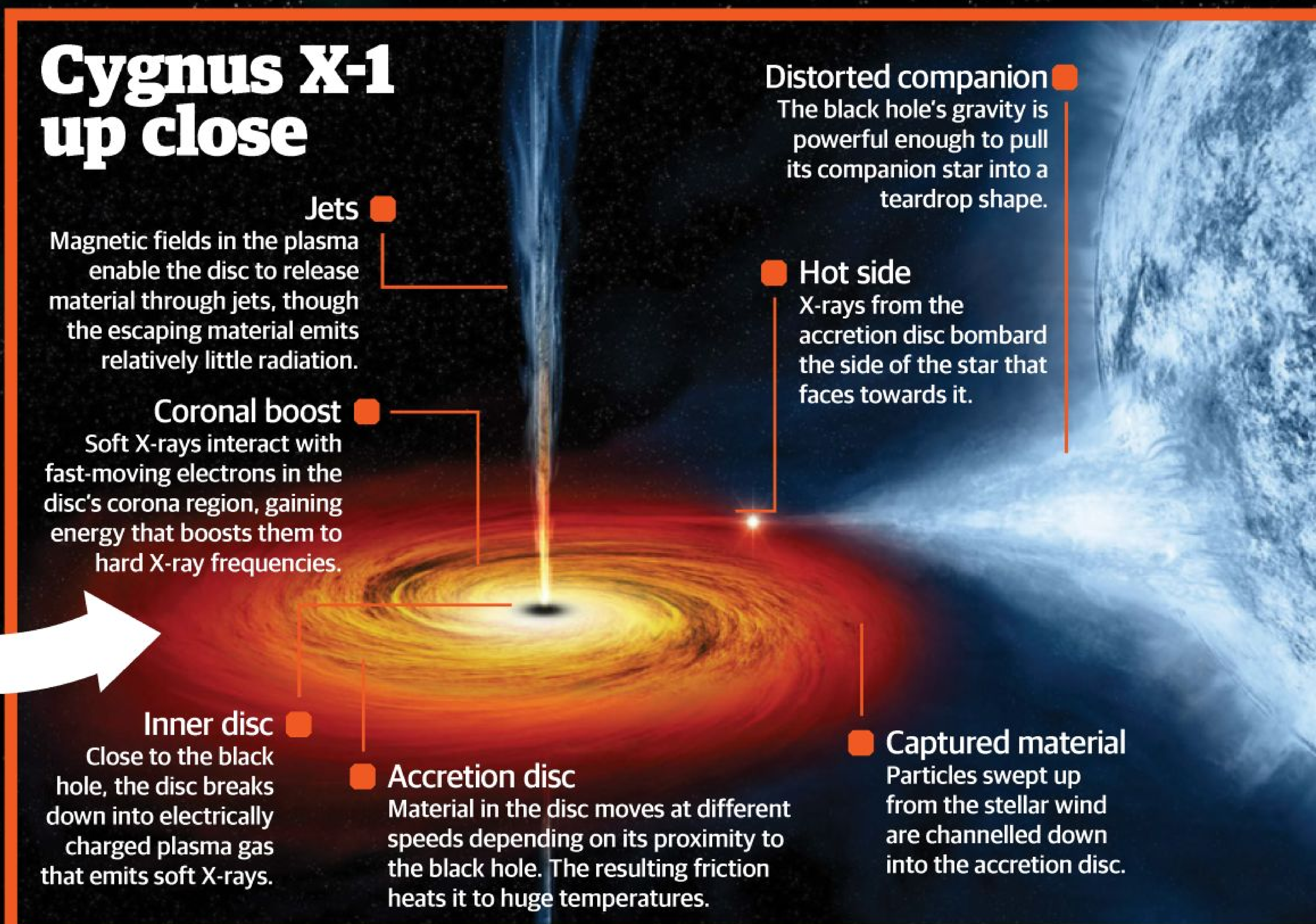
2. Faster evolution
The more-massive star used up its fuel faster and then swelled to an enormous size, its surface cooling as it became a red supergiant. At this time the less-massive HD 226868 may have pulled gas away from its tenuous outer layers.

3. Supernova!
Eventually the more-massive star could shine no longer and detonated in a spectacular supernova. The intensity of the explosion is still under debate and it may have actually been more of an implosion.

4. Aftermath
A new-born black hole emerged from the debris of the supernova explosion, still retaining substantial mass and locked in orbit with its companion star.

5. Cygnus X-1 today
Thanks to the supernova, HD 226868 accumulated more mass, swelling in size and brightening. The black hole now starts to grow by pulling material from the stellar wind into a hot accretion disc.

Cygnus X-1 up close



Jets
Magnetic fields in the plasma enable the disc to release material through jets, though the escaping material emits relatively little radiation.

Coronal boost
Soft X-rays interact with fast-moving electrons in the disc's corona region, gaining energy that boosts them to hard X-ray frequencies.

Distorted companion
The black hole's gravity is powerful enough to pull its companion star into a teardrop shape.

Hot side
X-rays from the accretion disc bombard the side of the star that faces towards it.

Inner disc
Close to the black hole, the disc breaks down into electrically charged plasma gas that emits soft X-rays.

Accretion disc
Material in the disc moves at different speeds depending on its proximity to the black hole. The resulting friction heats it to huge temperatures.

Captured material
Particles swept up from the stellar wind are channelled down into the accretion disc.

Observing a black hole

Studying an object that lets no light escape is as tricky as it sounds, but innovative telescopes have unlocked unseen layers of space

As the nearest known black hole to Earth, Cygnus X-1 has been subjected to intensive study over five decades. Most of what we know has come from satellite-based observatories and particularly orbiting X-ray telescopes. The system is usually the brightest source of hard X-rays in the sky, but generating images from these presents unique challenges. For a start they're extremely hard to focus on, as when they hit a reflecting surface head-on, they tend to either be absorbed or pass straight through it.

Early X-ray astronomy satellites had very low directional resolution – in principle they consisted of a shielded X-ray detector with an open window at one end, so attempts to map the X-ray sky involved scanning and recording the directions from which X-rays entered the detector window.

Fortunately more-recent orbiting telescopes have transformed our view of the X-ray sky. Beginning with the German-led ROSAT satellite (launched in 1990), increasing use has been made of an instrument design first outlined in the 1950s by physicist Hans Wolter. These telescopes use conical metal mirrors whose surfaces lie at fairly shallow angles to the incoming radiation, creating a situation in which X-rays ricochet off the surface and are deflected towards a focus point. By using several sets of concentric mirrors nested within one another, it's possible to form an image of a moderately large area of the sky, which can then be recorded using a solid-state detector fairly similar to the CCDs used in visible-light cameras.

The latest and most-sophisticated X-ray instruments to turn their attention towards Cygnus X-1 are NASA's Chandra X-ray Observatory and the European Space Agency's XMM-Newton (X-ray Multi-Mirror) spacecraft. Both were launched in 1999 and are still operational after a decade and a half in orbit. Chandra has a single telescope assembly using four pairs of nested mirrors to focus X-rays from a small part of the sky at high resolution. XMM-Newton, in contrast, uses no fewer than three separate telescopes with 58 individual mirrors in each to focus X-rays with a variety of different wavelengths, imaging larger areas of the sky than Chandra at lower resolution. Both telescopes also carry spectrometers capable of splitting and analysing X-rays from individual objects according to their energies.

Using observations from Chandra, XMM-Newton and other telescopes, in 2011 astronomers produced the most detailed analysis of the Cygnus X-1 system yet. Radio telescope measurements first pin-pointed the system's position in the sky as seen from opposite sides of Earth's orbit. The slight difference caused by our shifting point of view (an effect called parallax) was used to calculate the system's distance with unprecedented precision, putting it 6,070 light years from Earth. Combined with the optical spectroscopy of the companion star, this enabled researchers to determine that the black hole's mass at 14.8 times the Sun's, and that it moves through its region of space at a fairly sedate speed of about nine kilometres (5.6 miles) per second.

Finally, X-ray studies confirmed the general structure of the system and determined the black hole's rotation rate with unprecedented accuracy, revealing that it spins roughly 800 times a second – close to the maximum theoretical limit.

The sudden loss of mass associated with a traditional supernova explosion has a tendency to give binary systems a kick that throws them across space at high speed and also tends to reduce the speed with which the collapsed stellar core rotates. Cygnus X-1's combination of rapid rotation and slow speed through space suggest it may have formed in another way – a stellar implosion, rather than a true supernova explosion, in which the collapsing black hole simply consumed its progenitor star from within.

If the black hole really did form in this way, it would be the first confirmed example of this kind of highly unusual stellar cataclysm and yet another reason to study the system. Whatever the truth, it seems certain that, five decades on from its discovery and after being the subject of more than a thousand scientific papers, Cygnus' most famous object isn't ready for its swan song just yet.

Mission profile

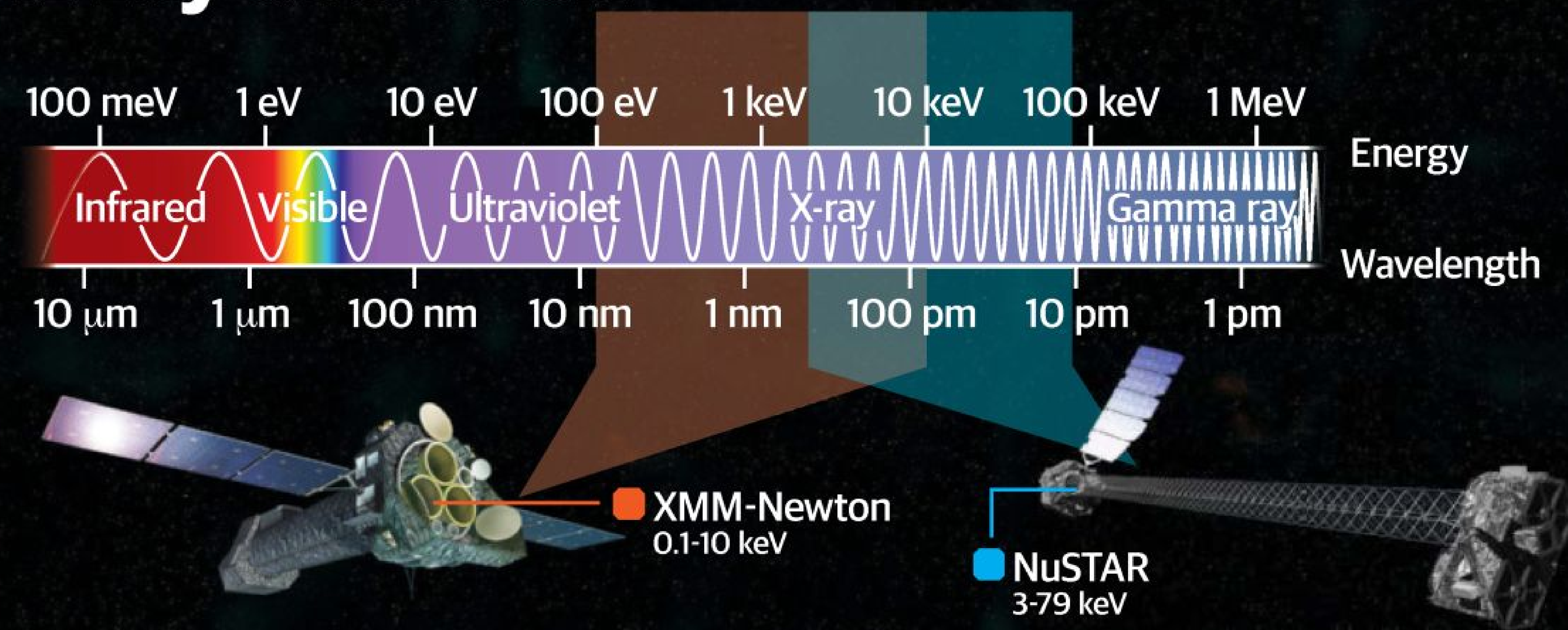
XMM-NEWTON

Launch: 10 December 1999
Launch vehicle: Ariane 5
Mass: 3,800kg (8,380lbs)
Length: 10m (33ft)
Orbit type: Elliptical, 7,000-114,000km (4,350-71,000 miles) from Earth.
Earliest deorbit date: Unknown

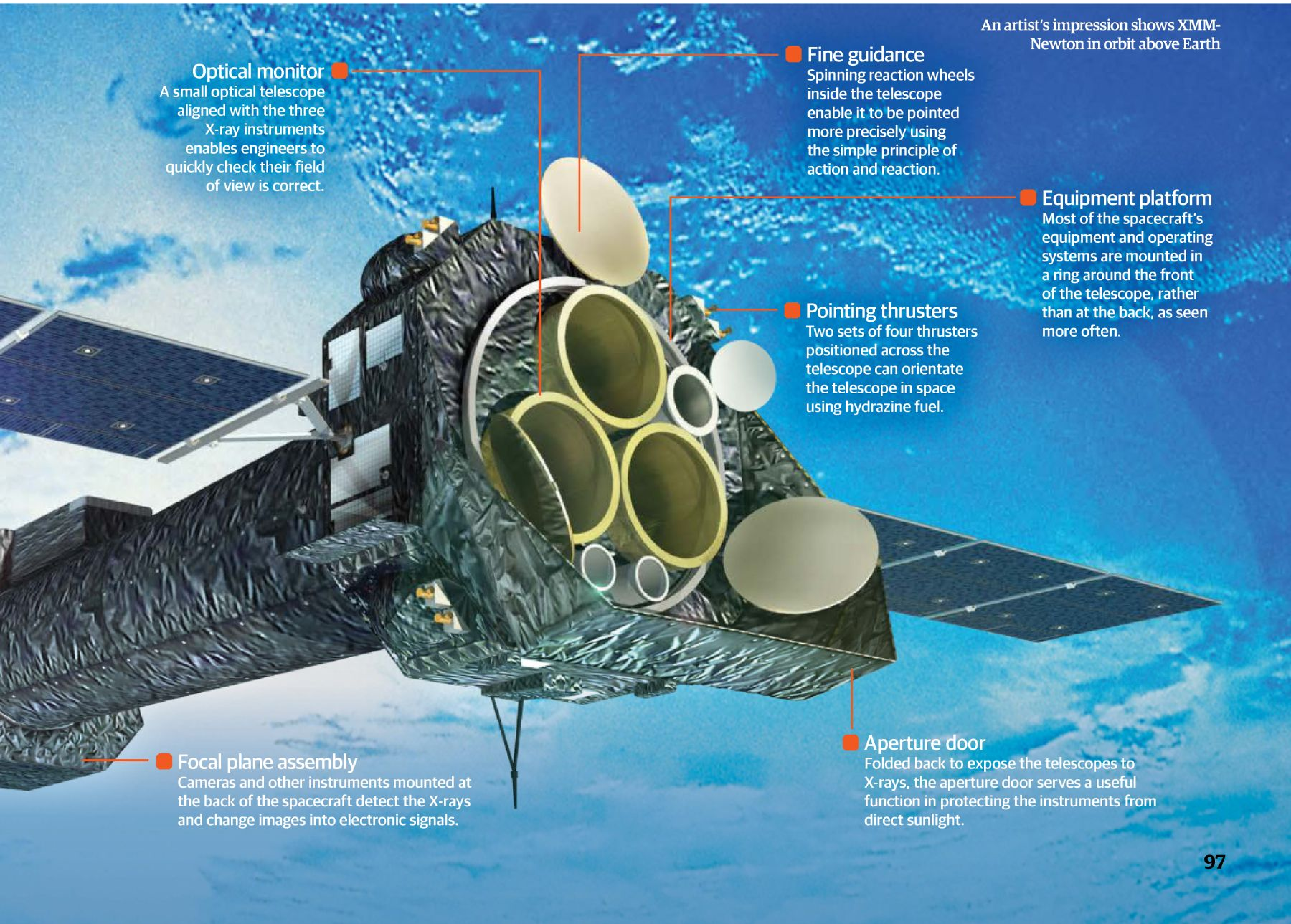
XMM-Newton's key discoveries include X-ray emissions used to identify some of the most distant galaxy clusters known, information about a host of extreme binary systems such as Cygnus X-1 and so-far-unexplained new sources of X-rays in far-off space.

XMM-Newton undergoes testing at the European Space Research and Technology Center in the Netherlands

X-ray detection



X-ray wavelengths range from around ten nanometres at their longest, down to just ten picometres (1,000 times shorter) at their shortest. The shorter the wavelength of an X-ray photon, the more energy it packs in and X-ray energies range from 100 electronvolts (eV) up to 100 kiloelectronvolts (keV) – the standard units of energy measurement in everyday situations. XMM-Newton images X-rays with energies of up to ten keV, covering all soft X-rays and many hard X-rays. NASA's NuSTAR telescope was built to detect even the higher energies associated with phenomena such as supermassive black holes – monsters millions of times more massive than Cygnus X-1.



An artist's impression shows XMM-Newton in orbit above Earth

Up close with a monster singularity

The new telescope project that hopes to teach us more about black holes by uniting observatories around the world for a closer look

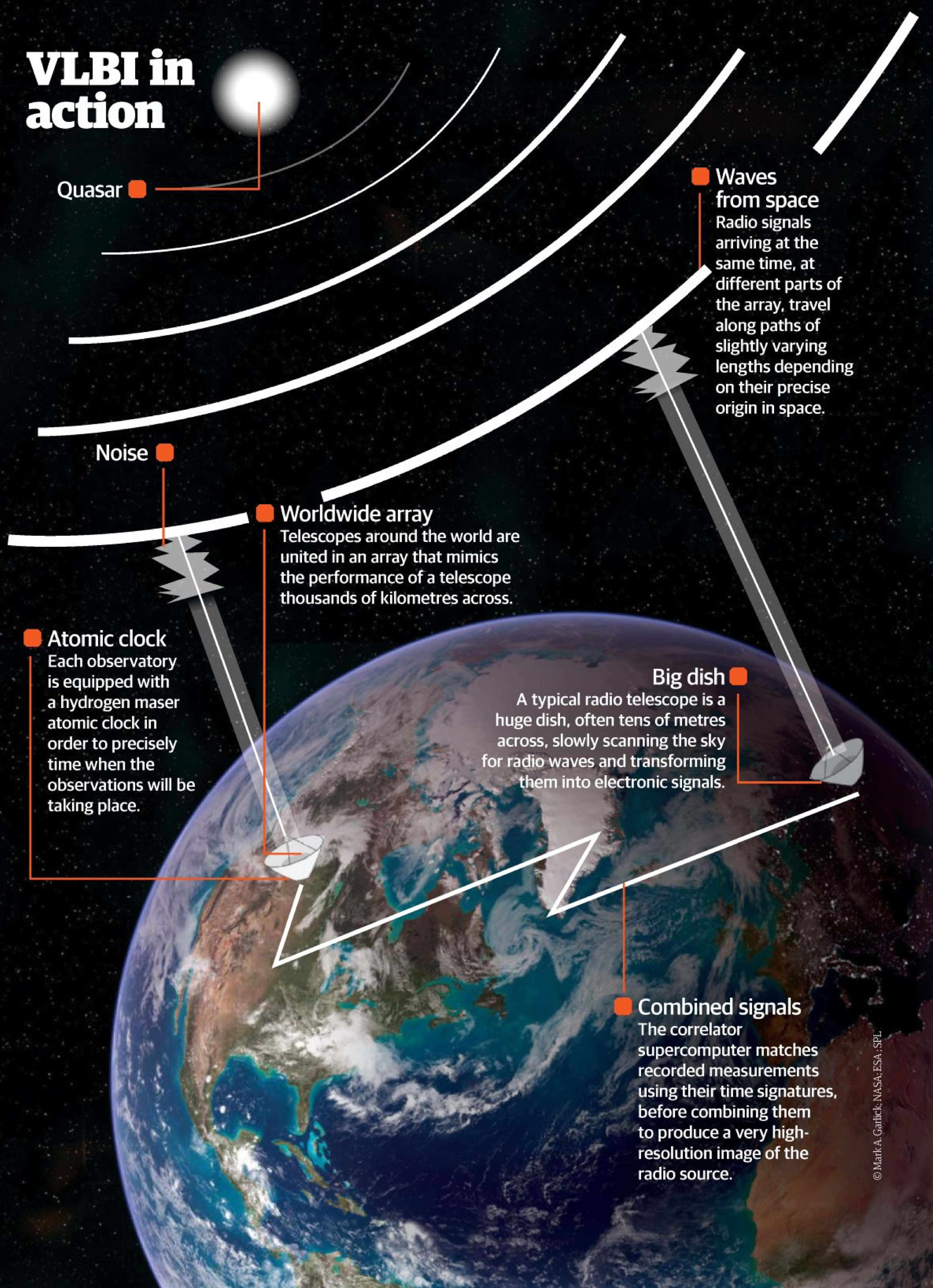
Cygnus X-1 might be the nearest black hole and the first to be discovered, but it's no longer the most famous – that title goes to Sagittarius A*, a supermassive black hole with the mass of over 4 million Suns that lies at the centre of our galaxy.

First hypothesised in the early 1970s, this black hole behemoth's existence was confirmed in 2002 when astronomers measured nearby stars orbiting it at high speed. While stellar-mass black holes typically have event horizons just a few tens of kilometres across, Sagittarius A* is many times the size of the Sun. This means that, even across a distance of 26,000 light years, it offers our best hope for observing a black hole directly.

Unfortunately this supermassive singularity long ago swept the region of space around it clear of substantial material, so while it can certainly emit X-rays when occasional debris strays into its path, at the moment it remains frustratingly placid. The only radiation coming from the region takes the form of infrared and radio waves produced as small amounts of gas sift gently into the black hole.

These long-wavelength rays present a huge challenge to astronomers trying to see the intricate details of Sagittarius A*. For a given diameter of telescope, they produce much lower-resolution images than visible light or X-rays, so the only solution is to go big. For an object as small and distant as this, that means a telescope the size of the Earth. The Event Horizon Telescope (EHT) is an international project aimed at linking existing radio telescopes around the world into a huge array with the power to resolve objects down to the apparent diameter of an orange on the surface of the Moon. The team behind it hopes to detect phenomena such as the predicted shadow created as radiation is deflected by the black hole's gravity. If they succeed, they may be able to extend the technique into space, targeting far smaller objects like Cygnus X-1.

The precise shape of the black hole's shadow will answer questions about its properties and whether it strictly obeys the predictions of general relativity



The Event Horizon Telescope

The EHT will make use of a technique known as Very Long Baseline Interferometry (VLBI). This involves making precisely synchronised observations of the same object from widely separated telescopes: radio waves will have had to travel slightly different distances to reach each of the different observatories. By measuring the differences in the length of their paths, it's possible to synthesise an image with the level of detail that would be achieved by an enormous telescope. In practise, this form of VLBI is achieved by recording simultaneous observations at all the telescopes in the array, then bringing them together using a specialised supercomputer called a correlator.

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Life on ALIEN MOONS

Should we be looking at other planets, or on the satellites orbiting them? Dr. David Kipping talks about life on distant exomoons

The moons in our Solar System possess a variety of conditions, but could alien life be thriving under such extremes?

It's now almost 20 years since the first alien planet was discovered in orbit around a Sun-like star. Since then huge advances have led to the discovery of more than a thousand extrasolar planets, or exoplanets, which are now being catalogued. But for those who dream of finding abundant life in the universe, it's been a time of mixed blessings: the vast majority of planets discovered have proved to be gas giants inimical to life, often in orbits so close to their stars that their atmospheres are searing hot.

Fortunately, persistent searches and new techniques have begun to home in on more Earth-like, rocky planets, some of which even lie in the habitable zone where liquid water can exist on the surface. But astronomers are also turning their attention to another possible haven for life – the natural satellites that almost certainly orbit many extrasolar planets, nicknamed exomoons.

Considering the challenges involved in finding exoplanets, discovering their much smaller moons might seem like an impossible task, but that's what first attracted David Kipping of the Harvard-Smithsonian Center for Astrophysics to the challenge. "My interest started more from a dynamical perspective," he explains. "I was interested in the challenge of modelling these things, it's almost like why people want to climb Everest. By 2009 we were just starting to detect lots of transiting exoplanets – NASA's Kepler satellite had been launched with the promise of detecting Earth-sized planets and we naturally wondered whether, if we had a telescope that could find a rocky planet, that maybe it could also find rocky moons."

> "If we want to pin down the prospects for life in our galaxy, then we have to include the moons" **Dr David Kipping**

Kepler was the first satellite designed to use a new planet-hunting technique known as the transit method. Its telescope stared continuously at a packed starfield, watching for tell-tale dips in the brightness of individual stars, caused when orbiting planets transited (passed in front of them), blocking out a small amount of their light. While previous attempts to find exoplanets worked best for giant planets with enough mass to influence their parent star directly, even small, Earth-sized worlds passing in front of a star's disc should cause a transit effect – it's just a matter of looking in the right place at the right time, with sufficiently sensitive instruments.

Adapting this technique to search for even smaller moons is no easy task, but as leader of the Hunt for Exomoons with Kepler (HEK) project, Dr Kipping has thrown himself into it. "It's a very challenging problem, but we've pushed it from mere speculation into science now. We've developed techniques that should be able to find them, so now we're working on the next challenge, which is trying to actually find them and see whether they're like the moons of our own Solar System, or turn out to be something completely different."

According to our current understanding of the way planets form, at least one type of exomoon should be commonplace: each of our Solar System's giant planets formed with a dense ring of gas, ice and

The closer a planet lies to its star, the less likely it will hold a satellite. Hot Jupiters like HD 189733b are unlikely to have exomoons

debris in orbit around it, which rapidly coalesced to form a system of natural satellites. In some cases (for example Jupiter's four Galilean moons and Saturn's Titan), these moons are the size of small rocky planets in their own right, with complex features such as volcanoes, icy oceans and complicated atmospheres that make them intriguing targets in the search for life in our Solar System. In theory, similar moons should have formed alongside many of the extrasolar gas giants. These could offer potential havens for life.

"Everyone's familiar with that concept from science-fiction books and movies, even if they haven't heard the term exomoon before," continues Dr Kipping. "One interesting reason we might look for them is that we know that gas giant planets are very common and even gas giants within the habitable zone are very common.

"One of the big questions in astronomy right now is identifying the probability of Earth-like planets in the habitable zone," he elaborates. "Kepler's enabled us to quantify that term: there was a recent, very thorough analysis, which found that two per cent of Sun-like stars have a rocky planet in the habitable zone. Now you can think of that as either a very small or a very big number (because there are so many Sun-like stars in our galaxy), but the same study also found that eight per cent of Sun-like stars have a gas giant in the habitable zone. So if even one quarter of those giants have a rocky moon big enough to have an atmosphere, then there may very well be more habitable moons than planets. Maybe we're the freaks, living on a planet rather than a

moon! If we want to pin down the prospects for life in our galaxy, then we have to include the moons."

When it comes to satellites like our own, however, we can't be so confident, at least not yet. Earth's Moon formed in the aftermath of a giant interplanetary collision that shook the young Earth to its core, but as Dr Kipping says: "We have no idea whether that giant impact that created our Moon was a freak event, or the kind of thing that happens all the time – and with only one example in our Solar System, we just can't tell."

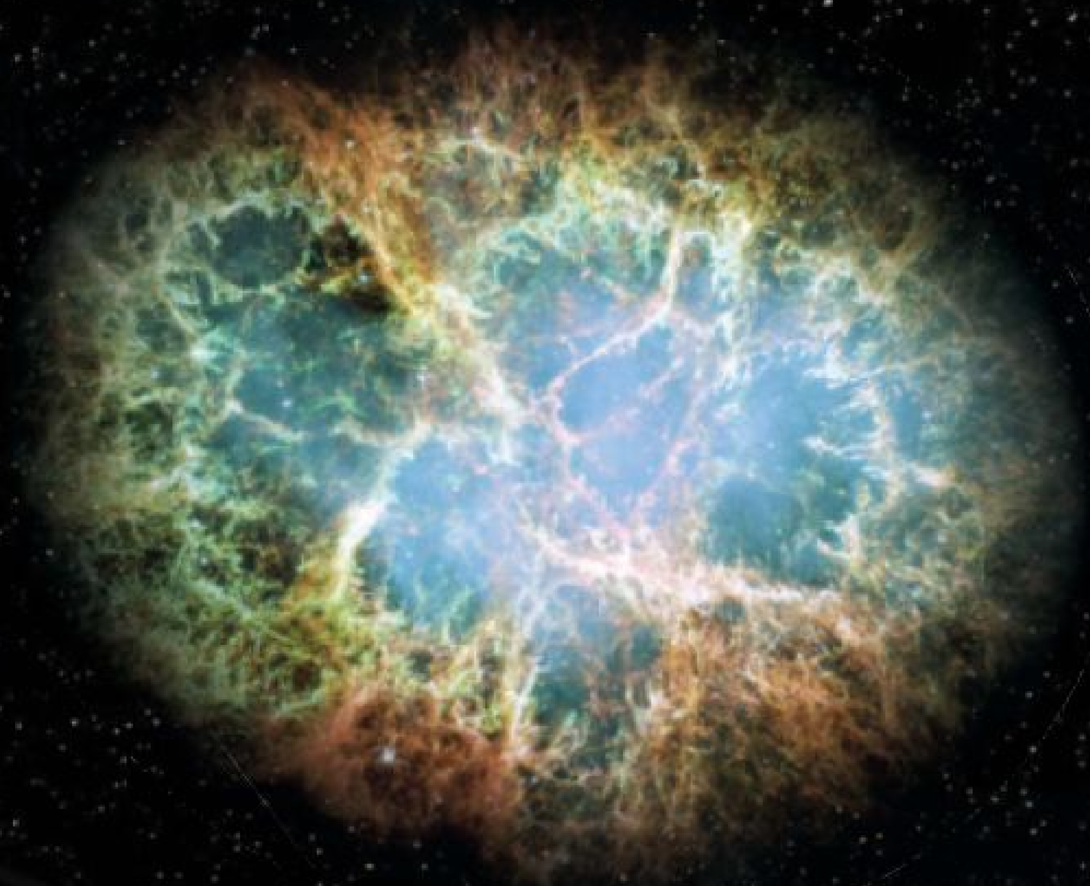
Dr Kipping points out another important reason to look for moons that are just like our own: "I call it extrinsic habitability. The presence of our Moon may have been beneficial to the emergence of life on Earth: it stabilises the axial tilt and climate and causes tides that mix the oceans and create tidal pools where life itself may have started. If we find an Earth twin, one of the first questions we'll ask is 'does it have a Moon twin?', because that's been so influential on our own planet."

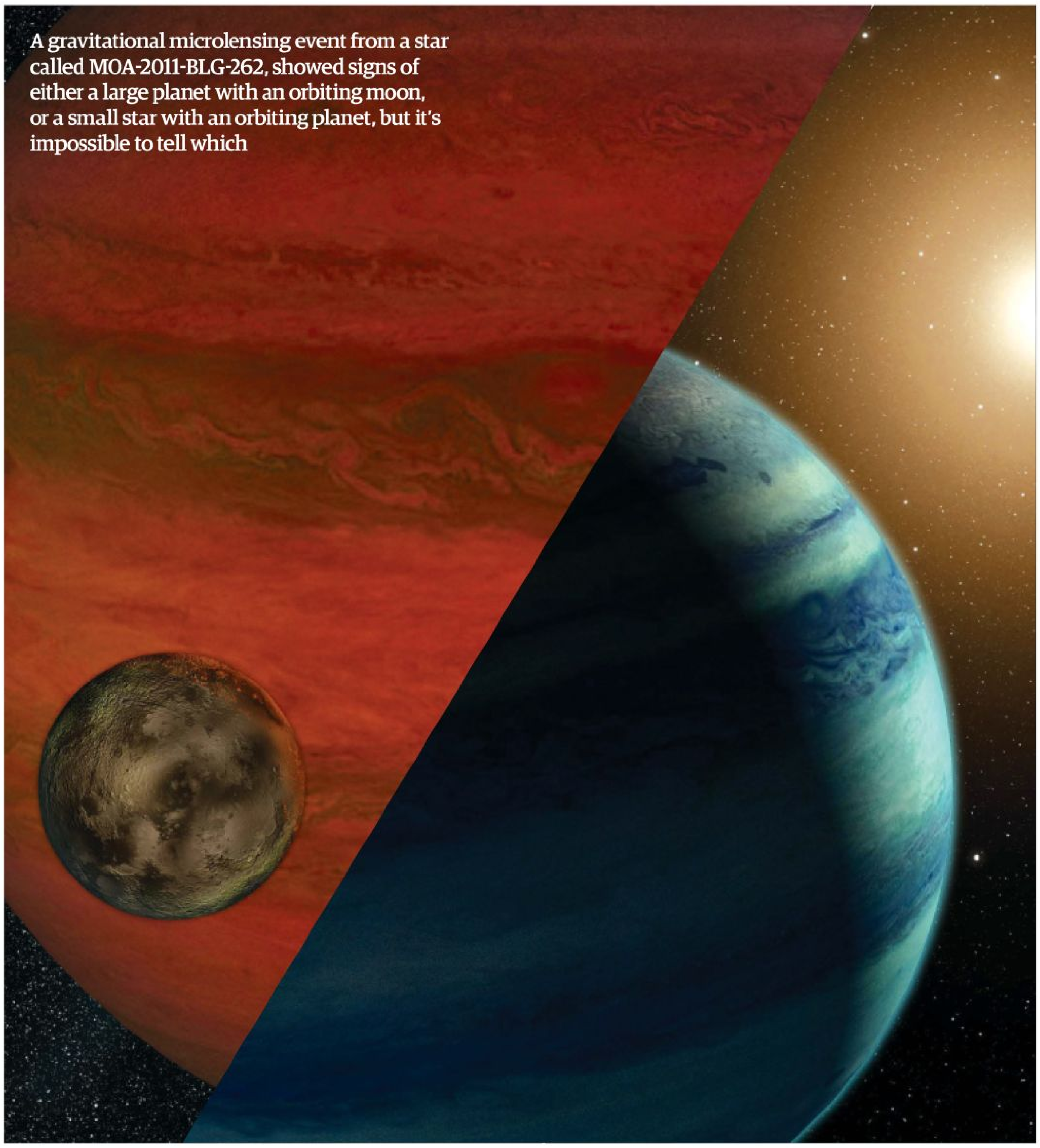
The HEK Project sifts data from Kepler looking for three different effects, each of which can reveal unique information about potential exomoons. Identifying periodic smaller transits caused by a satellite associated with a larger exoplanet is the most obvious of these (though it's a challenge that still stretches the sensitivity of Kepler's instruments). "Very simply, if you have a planet orbiting a star with the right alignment to our line of sight, you get a transit and if it has a moon, that will usually either appear to be leading or trailing behind the planet, so you will see an additional dip in the star's brightness when the moon blocks out light," explains Dr Kipping. "If you look over many orbits, then you'll see the dip from the moon at a different point in relation to the dip from the planet every time. It's not random – it's dictated by Kepler's laws of planetary motion. So, we basically model that in a computer, simulating a mini Solar System to see how it evolves and whether the little dips in the data can be explained by a moon, or maybe something else such as another exoplanet, or activity on the star itself."

The other effects are more subtle – changes in the timing of the exoplanet's own transit and differences in its duration, both caused by the planet wobbling under the influence of its moon. Dr Kipping illustrates this with an example that's much closer at hand: "If a distant alien were looking at Earth transiting the Sun, you might think it would see transit at identical intervals of about 365.256 days

The alien moon hunter

NASA's Kepler Space Telescope provided a wealth of raw data for experts searching for exomoons as it stared continuously towards a field of stars in the northern sky over four years, looking for tell-tale fluctuations in their brightness.





A gravitational microlensing event from a star called MOA-2011-BLG-262, showed signs of either a large planet with an orbiting moon, or a small star with an orbiting planet, but it's impossible to tell which

> "If you know the mass and size you can get the density – that tells you roughly what the moon is made of" **Dr David Kipping**

[Earth's official orbital period around the Sun], but in fact that transit could happen five minutes earlier or later. That's because the thing that actually orbits the Sun like clockwork is the centre of mass of the Earth-Moon system. The Earth and Moon are both orbiting around that point in space and although the centre of mass is deep inside the Earth [about 1,700 kilometres or 1,056 miles below the surface], Earth's wobble is enough to create variations of a few minutes.

"What's more, sometimes the planet seems to move across the star a bit quicker or a bit slower, because the tug of the Moon is causing its velocity through space to vary," Dr Kipping continues. "It's a bit like a pendulum: the duration effect is at its maximum when the timing effect is at its minimum and vice versa."

Putting all this information together could, in theory, lead to some impressive and revealing results: "Kepler can just about detect these kinds of timing variations, so you can then get the mass of the moon from the wobble of the planet and the size of the moon from the transit dip itself. If you know the mass and size you can get the density – that tells you roughly what the moon is made of. If it's an icy moon you get a density of maybe one or two grams per cubic centimetre, whereas if it's rocky then you're looking at about twice that."

In practise, of course, sifting the enormous amounts of data collected by Kepler between its launch in 2009 and eventual breakdown in 2013 is an exacting task. Based on its criteria of measuring over three transit events in front of a particular star, Kepler detected at least 4,000 planetary candidates.

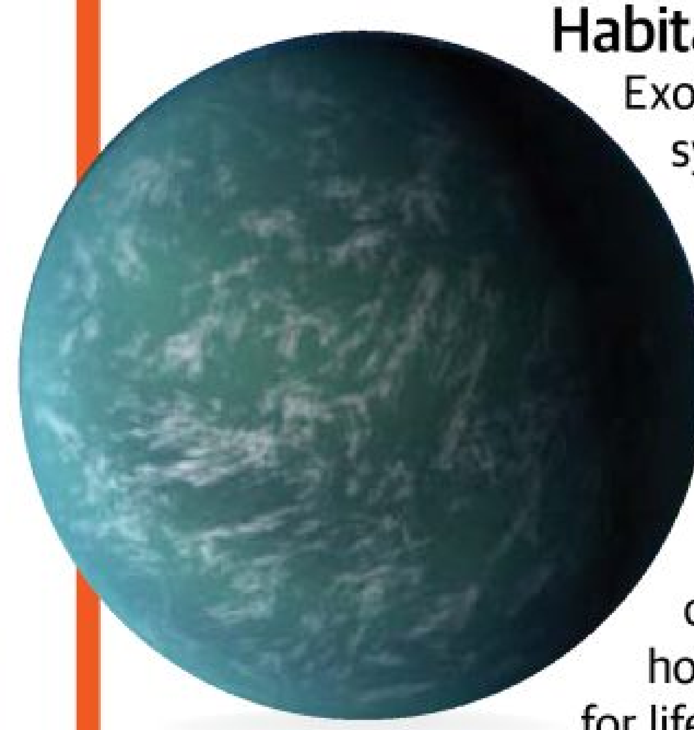
Unfortunately, most of these planets can be dismissed immediately as unlikely to have orbiting moons. The transit technique is naturally biased towards planets that are very close to their stars and many exoplanets orbit so close that their star's

The moon family portrait

Researchers group hypothetical exomoons into a number of different categories depending on their potential for life – hot, habitable, snowball and transient

Hot exomoons

Too close to a star and an exomoon may have an average temperature above the boiling point of water, making it highly unsuitable for any form of life.



Habitable exomoons

Exoplanets orbiting in a system's habitable zone (where liquid water can persist on a planet's surface) still need sufficient gravity to trap an atmosphere that regulates their temperature. If these conditions are met, however, the prospects for life are promising.

Snowball exomoons

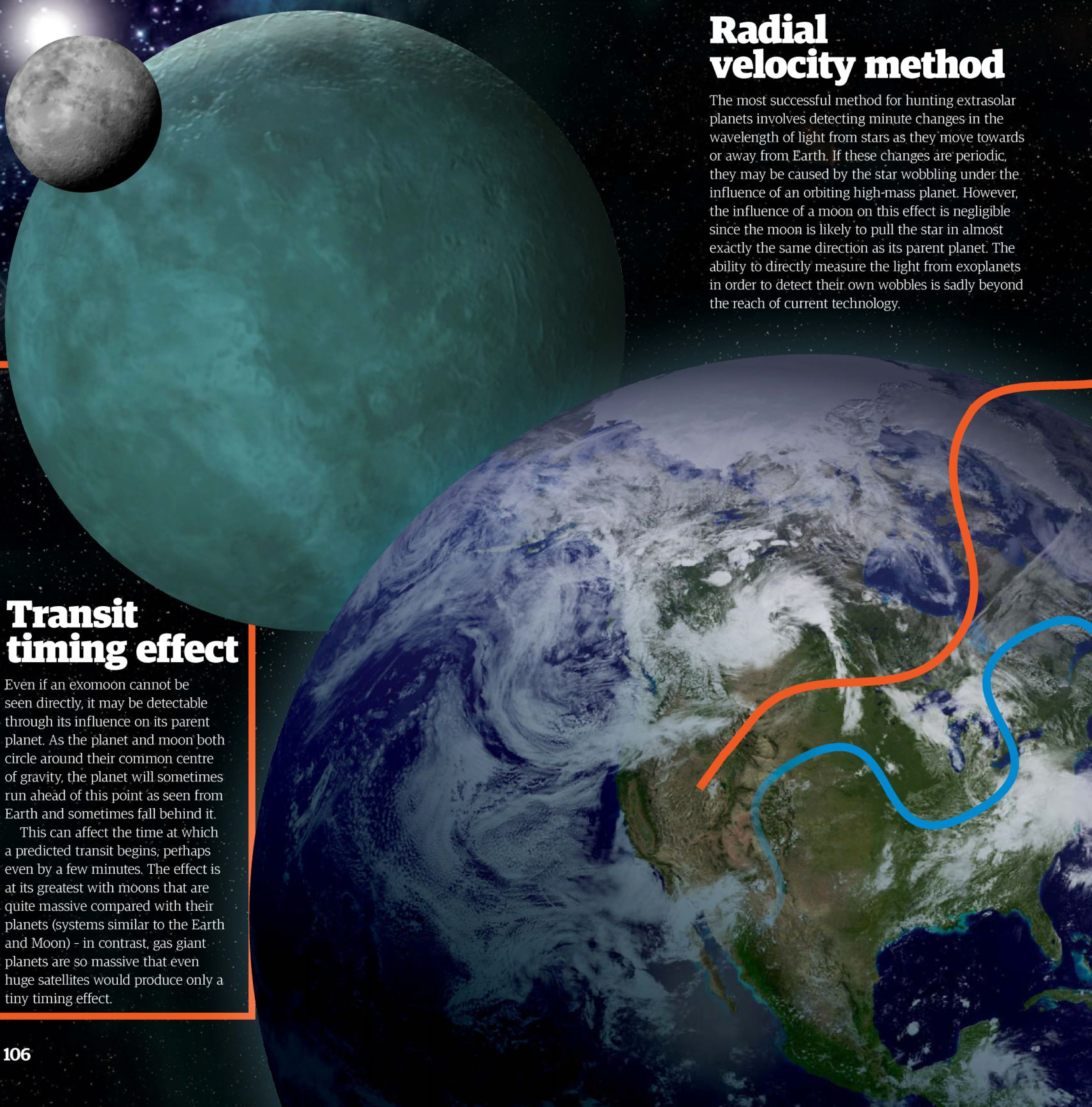
Moons formed in the outer reaches of an alien solar system are likely to be dominated by ice. They will remain deep-frozen unless heated by tides from their parent planet – again these are unlikely to be habitats for life.

Transient exomoons

Moons of planets with elliptical orbits might be habitable for most of their planet's year, but can experience hot or snowball periods as they venture too close to their star, or too far from its life-giving heat.

How to find an exomoon

Locating a companion to a distant exoplanet can be tricky, but astronomers have a few tricks up their sleeves



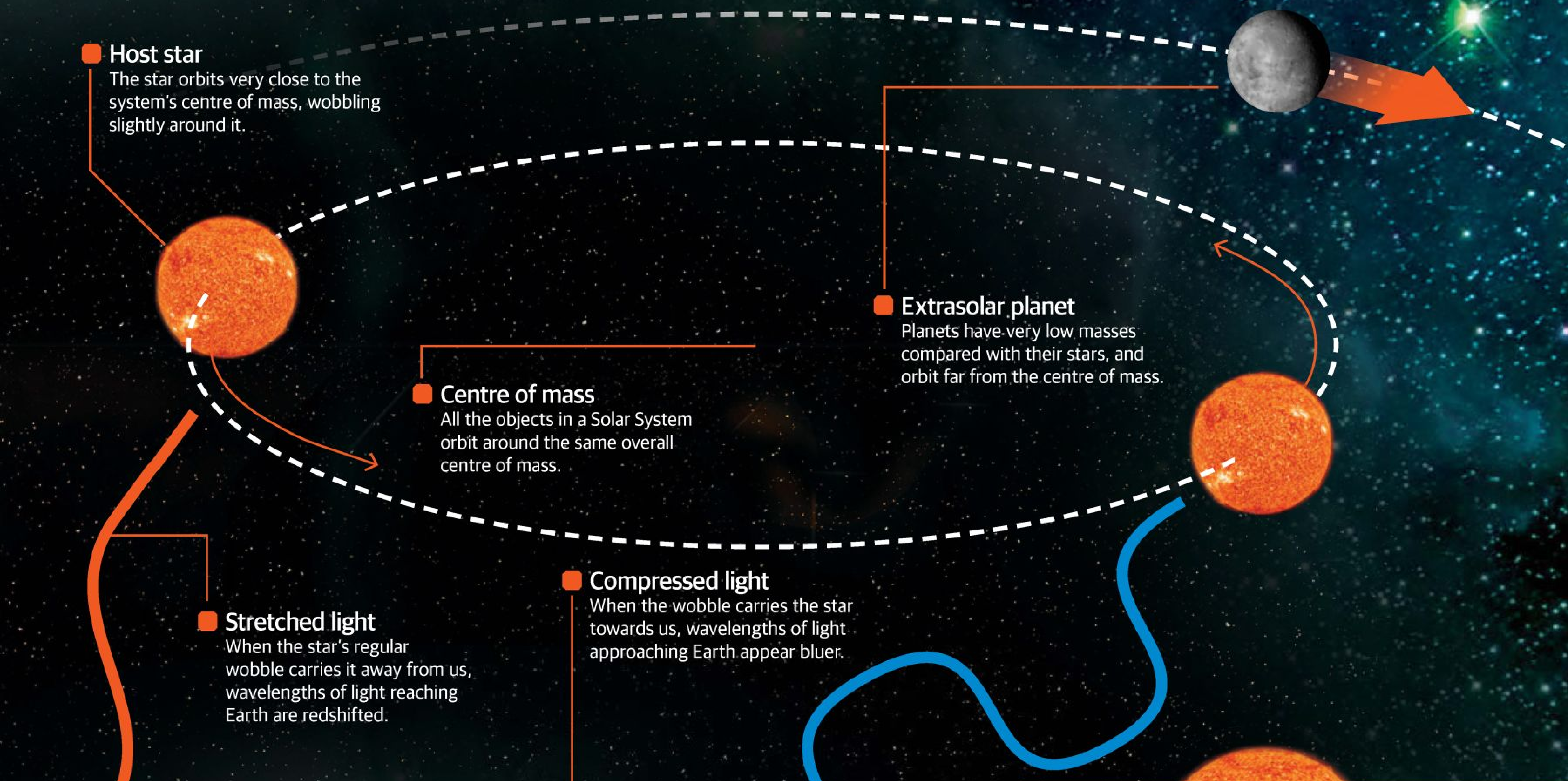
Radial velocity method

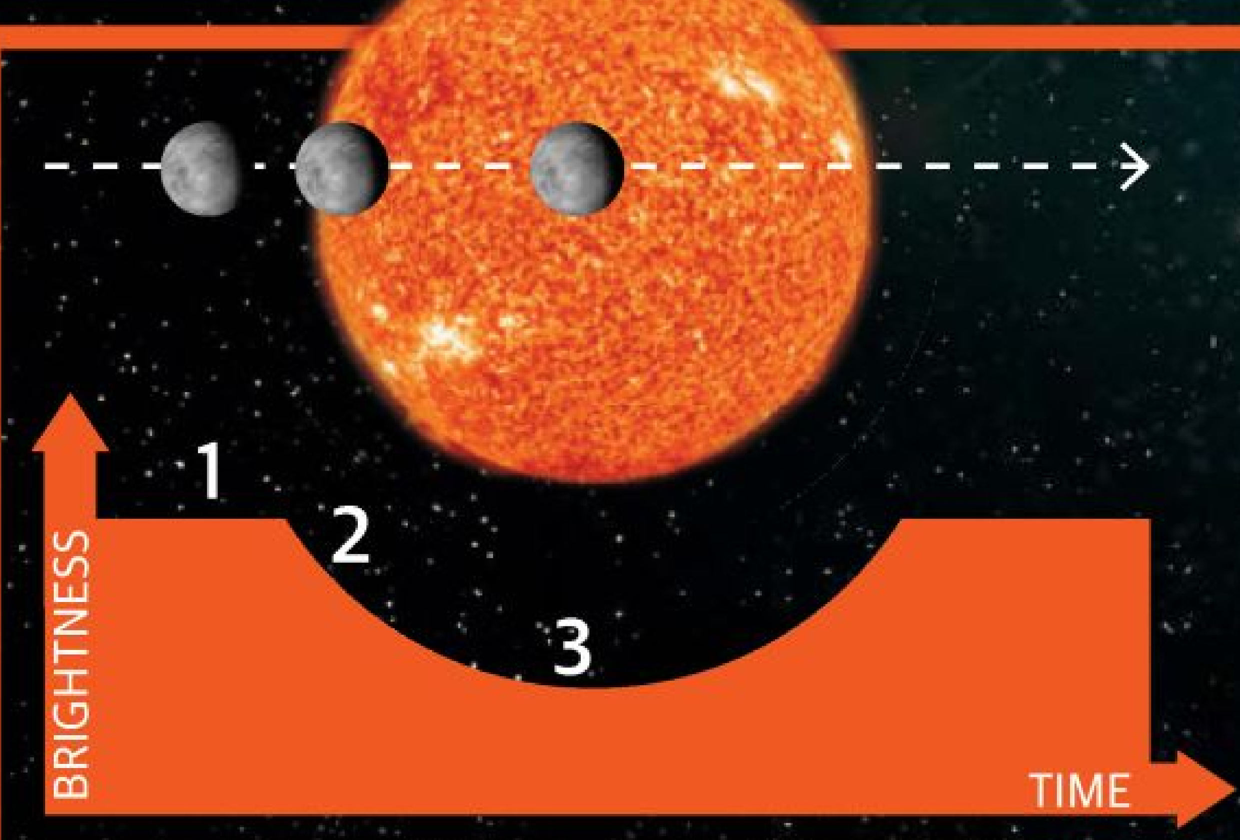
The most successful method for hunting extrasolar planets involves detecting minute changes in the wavelength of light from stars as they move towards or away from Earth. If these changes are periodic, they may be caused by the star wobbling under the influence of an orbiting high-mass planet. However, the influence of a moon on this effect is negligible since the moon is likely to pull the star in almost exactly the same direction as its parent planet. The ability to directly measure the light from exoplanets in order to detect their own wobbles is sadly beyond the reach of current technology.

Transit timing effect

Even if an exomoon cannot be seen directly, it may be detectable through its influence on its parent planet. As the planet and moon both circle around their common centre of gravity, the planet will sometimes run ahead of this point as seen from Earth and sometimes fall behind it.

This can affect the time at which a predicted transit begins, perhaps even by a few minutes. The effect is at its greatest with moons that are quite massive compared with their planets (systems similar to the Earth and Moon) - in contrast, gas giant planets are so massive that even huge satellites would produce only a tiny timing effect.





Transit method

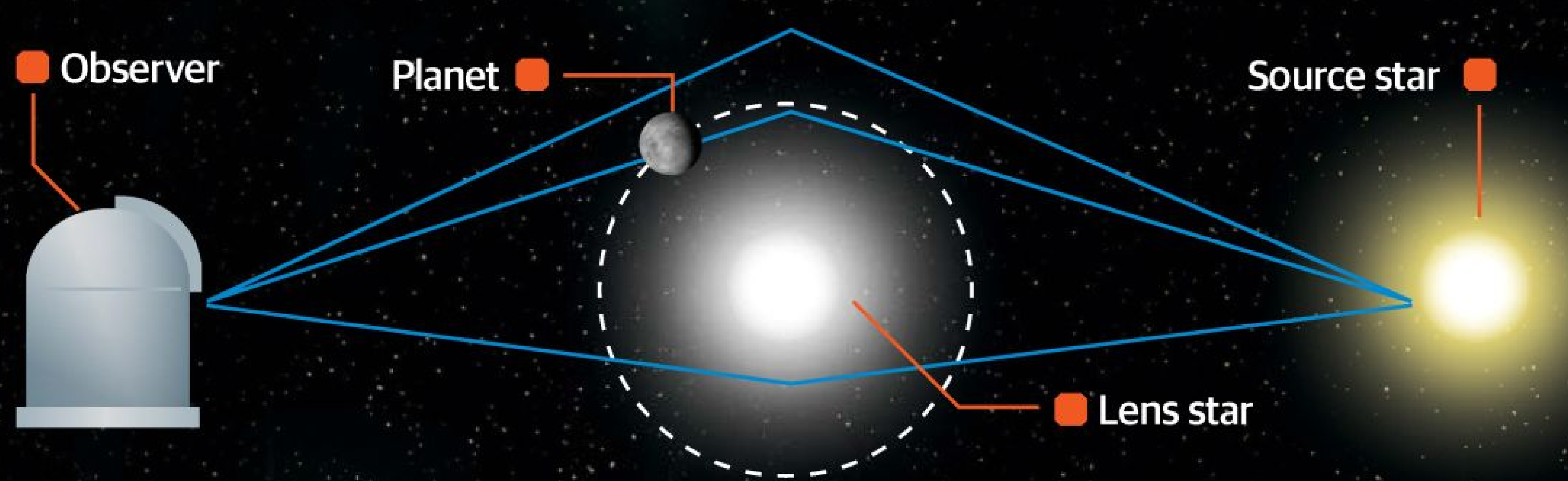
The transit technique looks for dips in a star's brightness as other objects pass in front of it - periodic and sudden changes in its light output can be linked to orbiting exoplanets and their moons.

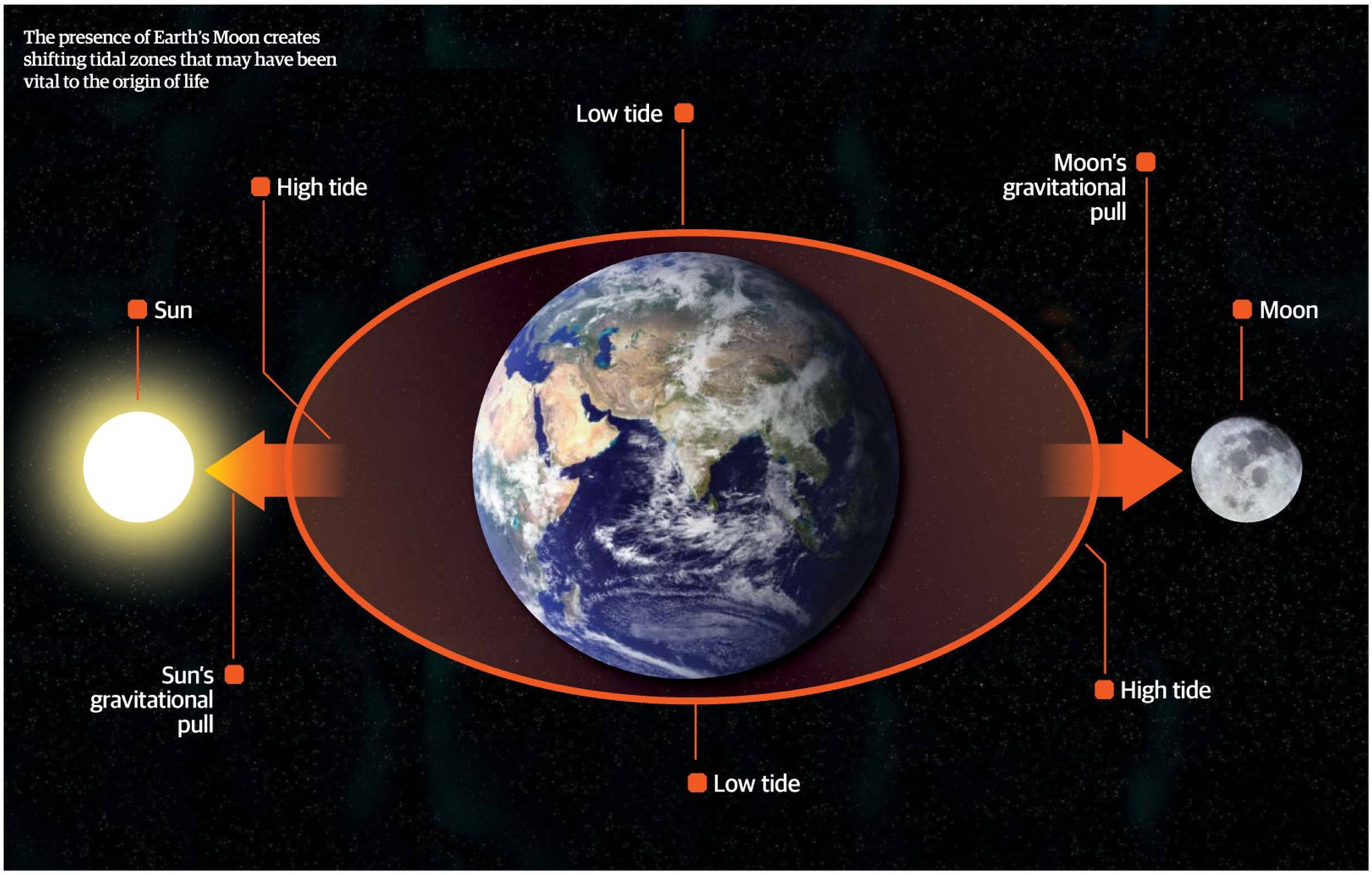
The method is biased towards detecting larger objects in orbits close to their stars, but not as badly as the radial velocity technique is biased towards high-mass planets. Looking for small additional dips associated with planetary transits is the obvious way to detect exomoons, but it requires close study and a satellite telescope above atmospheric light absorption.

Microlensing

This technique is almost the opposite of the transit effect - it involves looking for a brief brightening in a star's light as an object (such as a planet orbiting another star) passing in front of it bends and boosts its light through the affect of gravitational lensing.

In theory this method can detect less-massive objects than the traditional transit method, as well as spot differences in the lensing effect caused by the presence of exomoons. However, such events require precise alignments and tend to be one-offs - analysis may produce candidate exoplanets and exomoons, but it's almost impossible to confirm their existence with follow-up observations.





"I can't believe nature doesn't build moons frequently – it has a much greater imagination than ourselves" Dr David Kipping

gravity would simply rip any hypothetical moons out of orbit. In fact, only about ten per cent of Kepler candidates orbit far enough from their stars to potentially hold satellites.

"These days, it might feel like Kepler planets are a dime a dozen, but the subset of these long-period planets are very special to us and very precious," Dr Kipping explains. "We believe it's worth studying each one of these with a fine tooth comb to look for moons because, whether we find them or not – if they're common or rare – the answer is going to be one of the most important in modern astronomy."

So, how is progress going? "We've studied about 20 of them so far, and at the moment we're doing about 40 per year, so by the end of this year we'll publish the results for about that many. I'm not going to give the game away, but our aim is to look through at least the 100 or 200 best candidates and once we've looked at that many, we can say something in statistical terms about how common or rare big moons are in the universe."

However, things aren't entirely straightforward, since the methods used by the HEK team rely on a relatively massive moon capable of influencing its parent planet. "In terms of sensitivity, the data is good enough for us to detect Earth-like moons or smaller in about half the cases we're studying," admits Kipping. "So after looking at those 200 or so exoplanets we should have a much better idea of how frequently moons form by the kind of giant impact process that created our own Moon."

Ironically, the most-common exomoons, those around gas giants, are also the hardest to conclusively detect. Though they might be massive in their own right, such moons are dwarfed by the mass of their planets and have only the tiniest affect on the timing or duration of transit events. "They're still quite big of course, so it might be possible to see just the transit signature, but you wouldn't get the timing effects or the mass," points out Dr Kipping. "Without that I think it would be very difficult to prove you had definitely found a genuine exomoon."

Dr Kipping remains hopeful for the prospect of finding Earth-like exoplanets and their moons: "I'm still very optimistic we'll find them in the next year or two. I can't believe nature doesn't build moons frequently – it has a much greater imagination than ourselves, as it's proved this over and over again." ●

The Kepler Space Telescope is equipped with a specialised CCD camera

The search for alien life on exomoons

Assuming that exomoons are found, the big question is whether they would have the potential to be habitable. Dr René Heller has carried out eye-opening work on the constraints that govern the habitability of these worlds

Could you tell us what first got you interested in searching for exomoons?
What I find interesting about moons is that they are so much more abundant than planets, at least in the Solar System. They are so diverse! Some of them have atmospheres, some have volcanoes, some have internal magnetic fields, some have subsurface oceans – one of them [Titan] even has clouds and rain. This suggests an enormous population of moons around the known extrasolar planets, some of which might fundamentally challenge our picture of planet and moon formation. I consider it almost natural that some of these strange moons have habitable environments.

You're mainly researching the properties of moons around gas giants?
Yes, so far I've mostly been interested in big moons around Jupiter-like planets. Theories suggest that the biggest planets have the biggest moons – the king of the moons in our own Solar System, Ganymede, orbits Jupiter and some extrasolar planets are even more-massive than Jupiter, so they might have moons as massive as Mars. If such a system orbited a Sun-like star at an Earth-like distance, the moon – though not the gas giant planet – could be habitable. Isn't that an absolutely fascinating possibility?

These kinds of moon might be more-common than worlds like our own Moon, but aren't they much more difficult to detect than the planets they orbit?
Using the standard dynamical strategies for moon-detection, moons around very massive planets are indeed hard to find – but if we consider the direct transit signature of the moon itself, then the moons around giant planets are actually very promising targets. A moon's own transit signal depends only on its diameter relative to the star – the larger it is, the larger the dip in the transit light curve. With the biggest planets hosting the largest moons, the search for a moon's own transit dip works actually best for moons around giant planets.

So what factors would influence the habitability of an exomoon?
Talking about the possibility of liquid water on the surface, rather than under a frozen ice sheet, a moon needs to be at least as massive as Mars in order to have a gravitational field that is strong enough to retain a substantial atmosphere for billions of years. An atmosphere is needed to enable moderate temperature variations between night and day, as well as to sustain some kind weathering and global water transport. Since atmospheres of moons cannot possibly be detected directly in the near future, the size and mass of a moon are fundamental to assess its habitability to begin with. Intriguingly, all the available exomoon-detection methods work best for bigger moons, so they are actually biased towards potentially habitable worlds.

Are there any other constraints to the areas you have to search within?
Beyond mass and size, stellar illumination plays a key role. Too close to the star and the moon might be in a runaway greenhouse state, similar to Venus, or may lose its atmosphere entirely due to thermal escape. Too far away and the moon's atmosphere will freeze out, similar to what has happened on Mars. So the stellar distance of the planet-moon system must be within a certain range, maybe in the so-called stellar habitable zone. But on top of that, a moon receives illumination from the planet – reflected starlight as well as the planet's own thermal emissions. What makes things even more interesting is the internal heat reservoir generated in the moon by tidal dissipation. If a moon isn't on a perfectly circular orbit, maybe because there are other moons causing gravitational perturbations, then the varying gravitational pull of the planet on the moon will knead the moon, heating it up through internal friction. The closer a moon to its planet, the stronger this tidal heating.

So just as in our Solar System, that could create a potentially habitable environment outside of the normal habitable zone. What chance do you think we have of proving such worlds exist?
If an exomoon can be detected, then its mass, its distance to the planet and maybe even its radius would be known by means of the methods that we use to search for them. A moon's mass and radius combined would give us an idea about its average density, which might enable us to classify it as a rocky, a water-rich, or an icy moon. So depending on the data quality, the basic moon characteristics, as well as the basic physical values of the planet and the star should come alongside the detection. These values alone should give us a reasonable evaluation of the possibility of a moon being habitable – they might be [found] in data from Kepler.

But answering the question of [whether or not] a moon is actually inhabited by some form of life would certainly be a task for the next generation of astronomers and astrobiologists, who would need to measure whether the moon has an atmosphere and liquid surface water. Currently available instruments wouldn't permit such studies, but they're possible in principle. Humanity just needs to decide to perform such investigations and then we need a bunch of very capable engineers.

By observing the very largest exoplanets, scientists expect to find the very largest exomoons, which could be habitable

Red dwarfs

They're tiny and too faint to see with the naked eye, so why are we straining to observe these ancient stars of the universe?

Space is no place for the agoraphobic: our Solar System alone is so vast and empty it makes the open sprawl of the original American prairie seem like the inside of a small cardboard box. The technology that enables us to see massive objects from billions of light years away tends to make us fixate on the really big stuff in space, such as R136a1, a Wolf-Rayet star found in the Tarantula nebula that's an estimated 265 solar masses and outshines our Sun with nearly nine million times its luminosity. Closer to home, just a few thousand light years away, there's VY Canis Majoris. This red hypergiant has an estimated mass of up to 35 times that of our Sun, but it's voluminous enough that if it were scaled down to fill the palm of your hand, the Sun would appear smaller than a grain of sand next to it.

We pore over and marvel at these huge and distant objects, but all the while there are millions of equally fascinating smaller stars within a stone's throw of our Solar System. You might think that these stellar relatives are so small, in comparison with the awe-inspiring stellar behemoths, that it's impossible to regard them as interesting. However, their stories are just as, if not more fascinating.

Just around the corner from the Sun is Proxima Centauri, the nearest star to our own at just over four light years away. It's an example of a red dwarf – a small star that sits on the bottom-right rung of the main sequence in the Hertzsprung-Russell diagram – a graphical tool, named after its astronomer creators Ejnar Hertzprung and Henry Norris Russell that enables scientists to classify stars according to certain characteristics such as their brightness, colour and stellar type. Red dwarf stars range in mass from a low of 0.075 up to 0.5 times the mass of the Sun and most are only a few times the diameter of Jupiter, the king of the planets in our Solar System. These pint-sized stars are made just like any other main sequence star – a cloud of dust and gas is pulled together by gravity and begins to spin. The swirling causes the material to clump closer to the centre and before too long it reaches a temperature at which fusion begins. Despite their slight size, however, their low mass means these mini stars are much more easily formed, so hugely outnumber every other star type in the Milky Way. It's possible they even make up the majority of the stellar population in other galaxies too. In fact, around 20 of the nearest 30 stars to Earth and up to three quarters of the stars in our galaxy are red dwarfs.

We've established that many of the stars in our universe not only vary in size, but in surface

"Despite their slight size, their low mass means these mini stars are much more easily formed, so hugely outnumber every other star type in the Milky Way"

Proxima Centauri shines bright through the Hubble Space Telescope in this recent image, but it's invisible to the naked eye. It's likely to remain a main sequence red dwarf for four trillion years

temperature. As a result, astronomers like to put them into categories, or spectral classes O, B, A, F, G, K, M, L, T, Y. Starting from the young, unbelievably hot blue O-type stars, the classification takes us through to stars like our Sun, the G-type yellow dwarfs, before ending at the extremely cool Y-type brown dwarfs. Of the nine classes, dubbed the Harvard Spectral Classification – a scheme named after Harvard college observatory where it was developed around 1910 – that many of the stars in our universe belong to, red dwarfs are designated as the progressively cooler M-types.

Proxima Centauri is a late M-class star with barely enough mass (12 per cent of the Sun's) to sustain the temperature and pressure necessary to create nuclear fusion at its core. It's around 200,000 kilometres (124,270 miles) in diameter, which makes it only a little larger than Jupiter – that itself has a diameter of 143,000 kilometres (88,860 miles). Like other red dwarfs, Proxima Centauri has a relatively low surface temperature in the region of 3,000 degrees Celsius (5,432 degrees Fahrenheit) and is burning through its supply of hydrogen inside and outside its core, which it formed with less rapidly.

In comparison, larger, more-heavyweight stars only manage to burn through the hydrogen found at their core before their lives are snuffed out. Since red dwarfs burn at such a low temperature, the result is that they are extremely faint – even as the closest known star to the Sun Proxima Centauri is only visible as an eleventh magnitude object, which is too faint to be seen from Earth even with binoculars. The star is even outshone by some that are hundreds, even thousands of light years away.

Red dwarfs like Proxima Centauri are both interesting and important to our understanding of the universe for several reasons. First, our own yellow dwarf (the Sun) has a volume that's proportional to its mass, because its matter behaves like gas under its immense gravity. With much lower M-class stars at the bottom end of main sequence, stellar matter is more able to resist gravity's effects and curious quantum influences come into play. Matter is said to be degenerate in these stars, so although Proxima Centauri is only about 1.5 times larger than Jupiter, it has over 120 times the mass of the gas giant.

Generally speaking the lifetime of a star will increase exponentially in inverse proportion to its mass. So, the brightest and most massive stars in the universe, the hypergiant O-types of several dozen solar masses or more, might last a few million years – a cosmological blink of an eye. They burn through their nuclear fuel at a terrific rate and bloom in volume before exploding in an energetic hypernova.

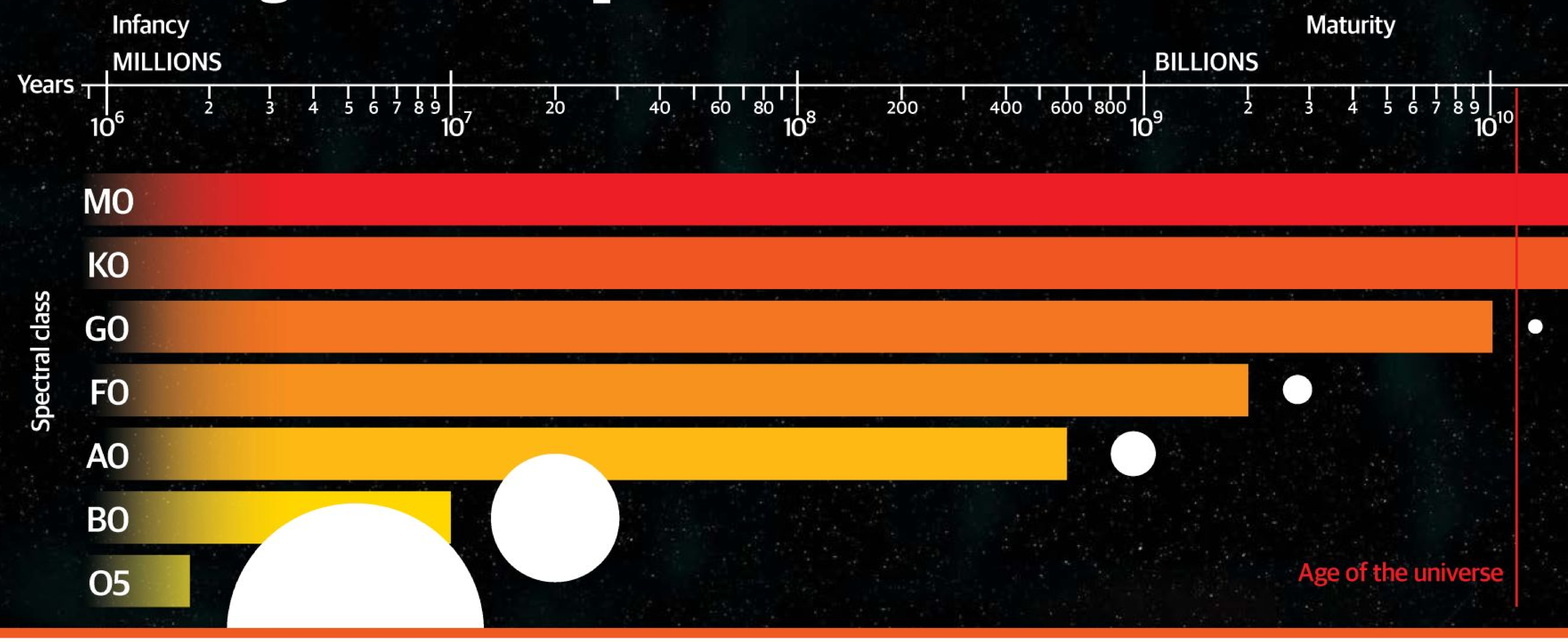
> "The sheer number of red dwarfs makes it unlikely that life hasn't existed around at least one of them"

Even stranger small stars

There is a class of substar whose mass falls below the lowest theoretical threshold at which a stellar object can sustain hydrogen fusion and so be considered a true star. Brown dwarfs straddle the gap between the biggest gas giants and smallest stars, with masses that range from about 80 times that of Jupiter down to a debated low threshold of about ten Jupiter masses. They are extremely dense, so despite being many times the mass of Jupiter, brown dwarfs are the same size as the gas giant.

The laws of quantum physics govern the huge density of some of the smallest and strangest stars in space. Neutron stars are often left by massive stars after a supernova. They can be several times the mass of the Sun, yet have a diameter of just ten kilometres (six miles).

How long do main sequence stars live?

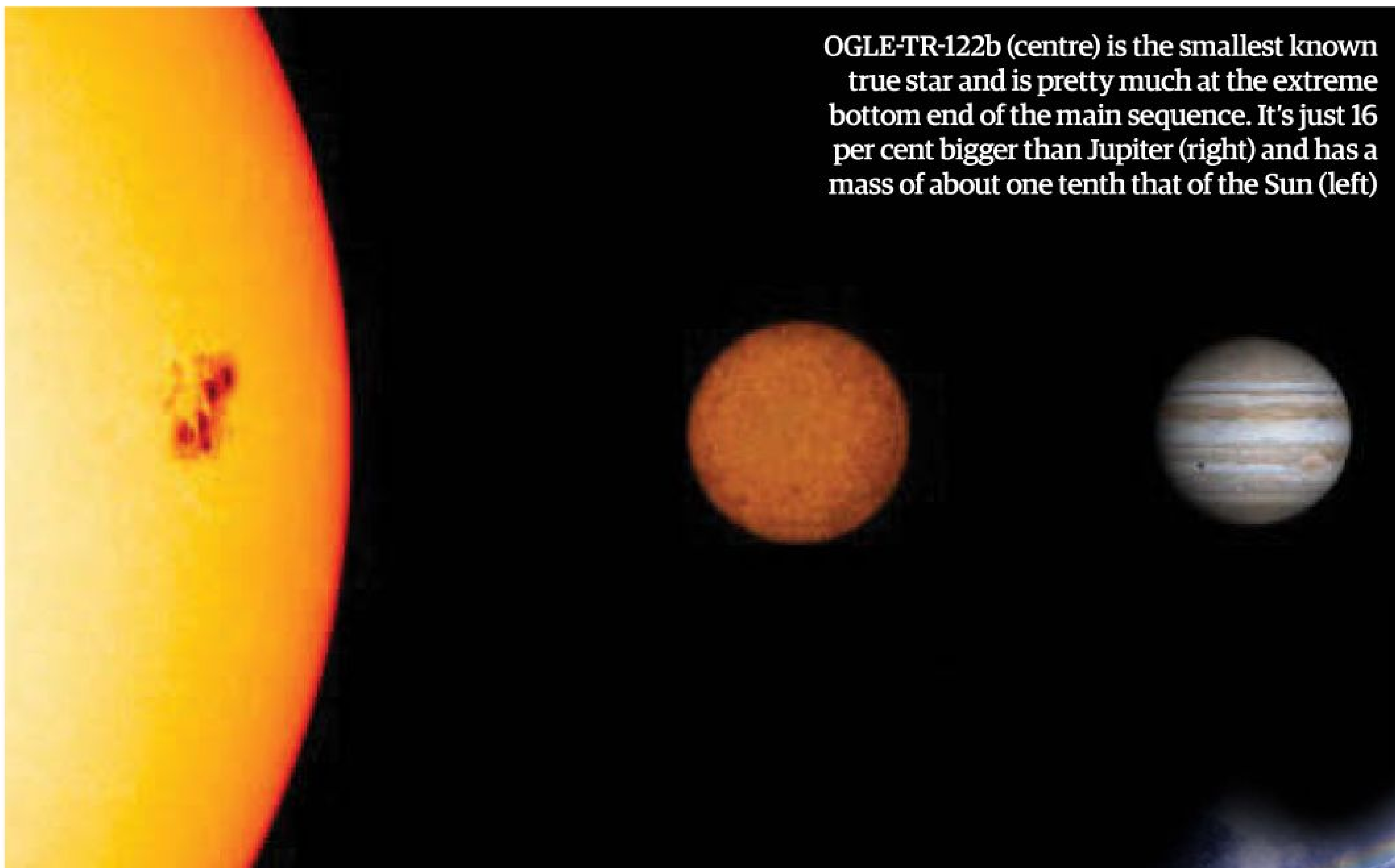


Our G-type Sun, which has been around for five billion years or so, will continue to use its remaining hydrogen for around another five billion years before it throws off its outer layers in huge mass ejections, leaving nothing but the white hot ember of its core behind to be seen.

We can see examples of stars at these final stages of their evolution throughout our galaxy. However, we're unable to see any dead or dying red dwarfs, because their lifetimes can run into hundreds of billions, even trillions of years, many times older than the current age of the universe. So the ultimate fate of these slow burners - gradually fading away as a white dwarf - is currently all theory.

In recent years known red dwarf stars have become the go-to objects for exoplanet-hunting telescopes, partly because there are so many of this type of star to observe and scientists think there is at least one exoplanet orbiting every red dwarf in our galaxy. Their long lifespans and stability also make it more likely that complex life could develop on an exoplanet orbiting a red dwarf. It took over 500 million years for the very simplest of single-celled life forms to appear after the formation of the Earth. Given that as an analogue, we're unlikely to find life on a planet orbiting an O-, B-, A- or even some F-type stars, whose lifespans tend to be far too short to nurture any form of life.

New exoplanet-spotting techniques and more-powerful telescopes are revealing planets all the time. Just recently, a NASA researcher discovered the first Earth-sized planet in the habitable zone of another system, one of five orbiting an M1-type red dwarf star. While it's the subject of some debate as to whether a planet that orbits this close to a red dwarf can also play host to life, the sheer number of red dwarfs makes it unlikely that life hasn't existed around at least one of them at some point in history. In any case, as one of the most numerous and yet difficult-to-observe types of star in the universe, these red dwarfs can only become more interesting to astronomers over time.

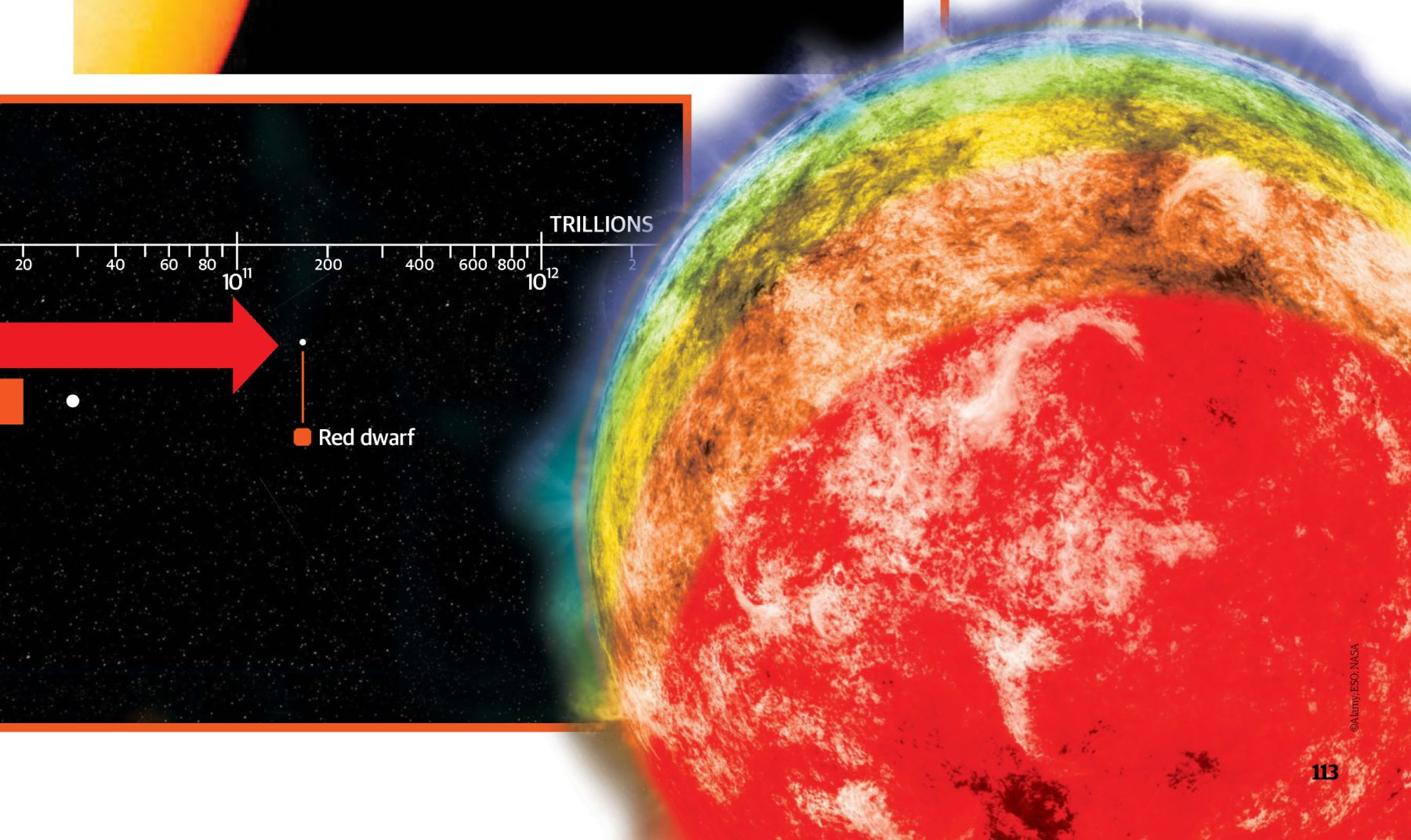


OGLE-TR-122b (centre) is the smallest known true star and is pretty much at the extreme bottom end of the main sequence. It's just 16 per cent bigger than Jupiter (right) and has a mass of about one tenth that of the Sun (left)

How many red dwarfs are there?

Percentage of main-sequence stars in the universe

- M (red dwarf) 76.45%
- K 12.1%
- G (the Sun) 7.6%
- F 3%
- A 0.6%
- B 0.13%
- O 0.00003%



Space Science

The nuts and bolts behind our knowledge of how the universe works

"It can release more energy in 10 seconds than our Sun will in its entire 10 billion years"

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Space radiation

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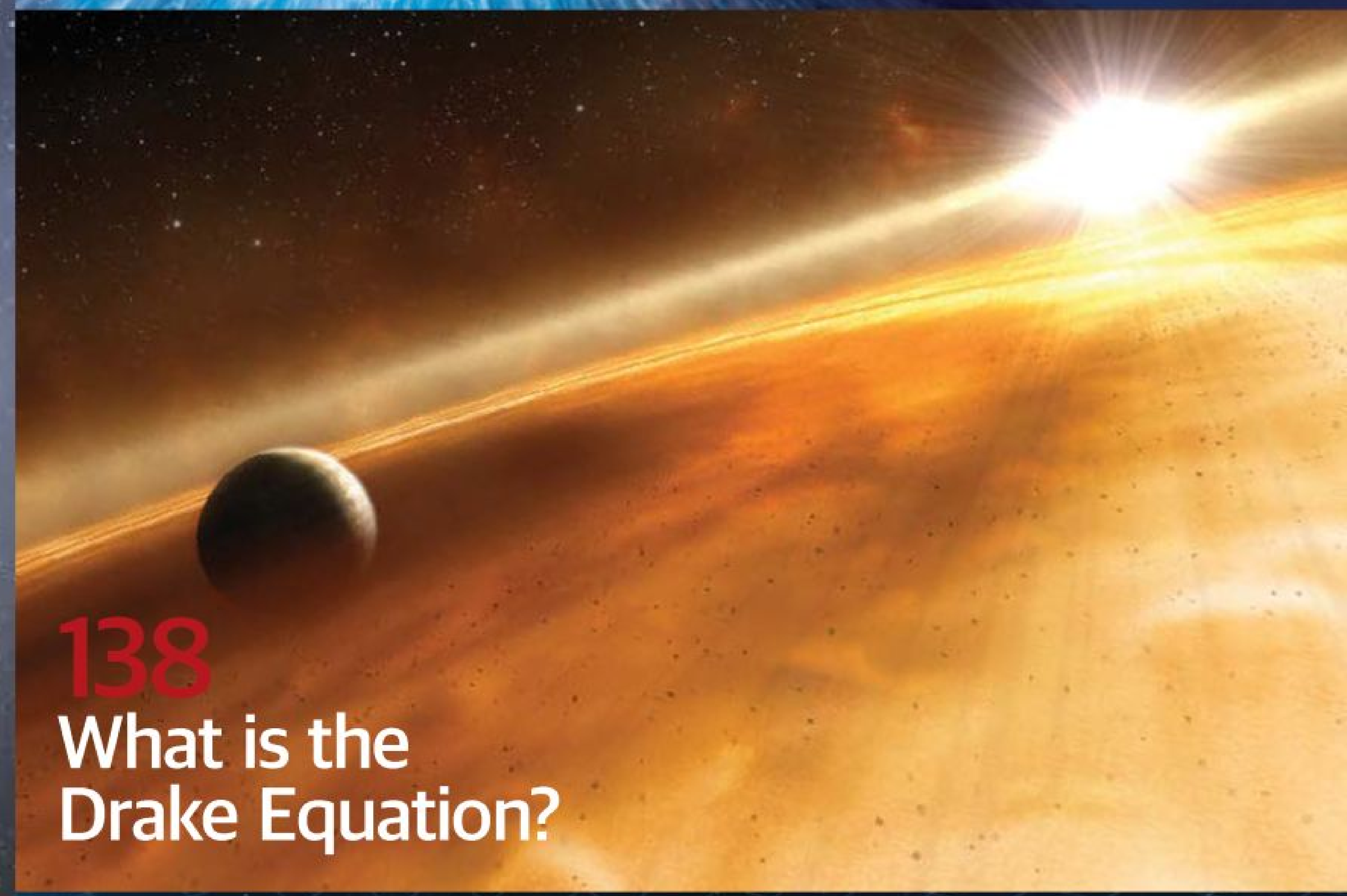
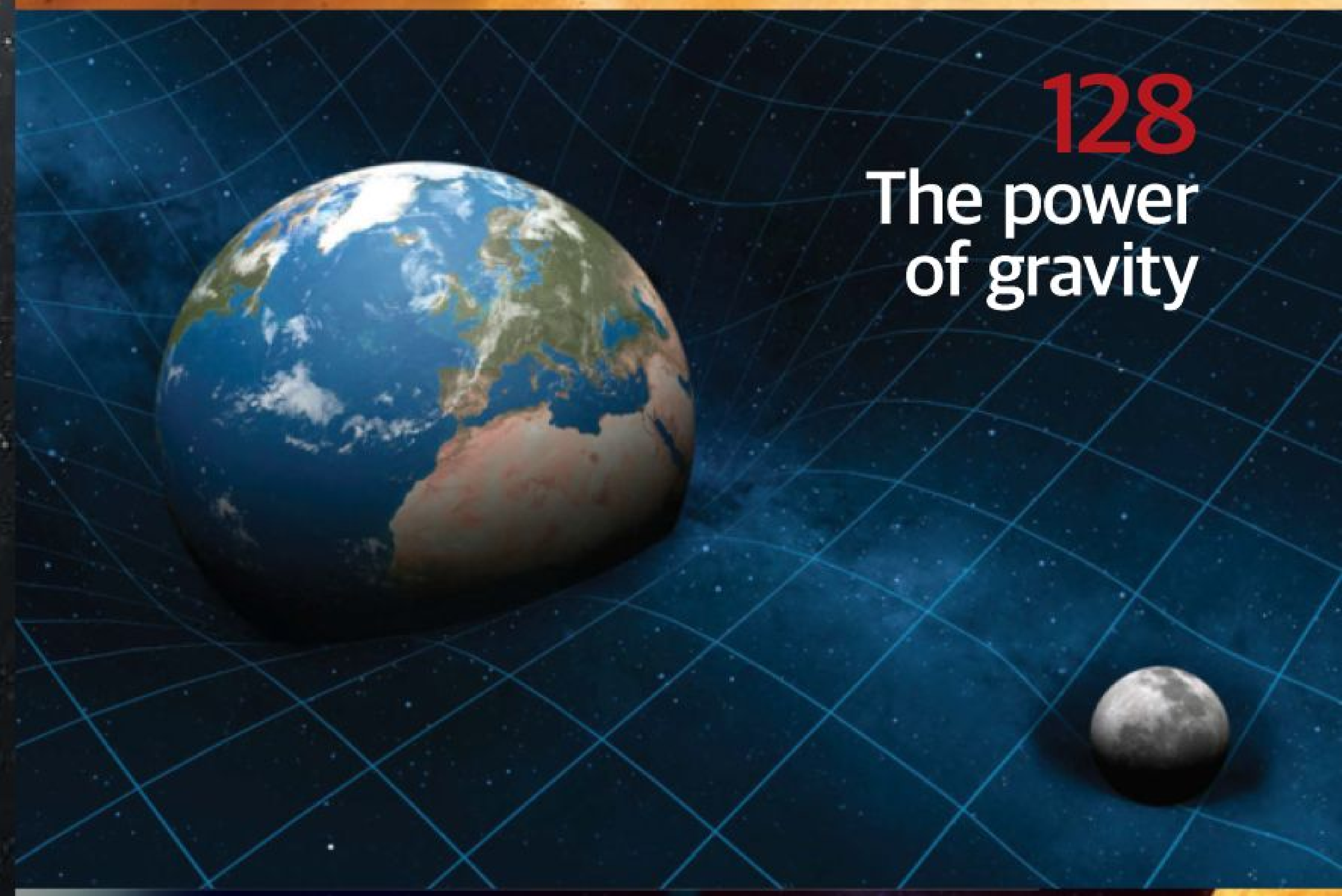




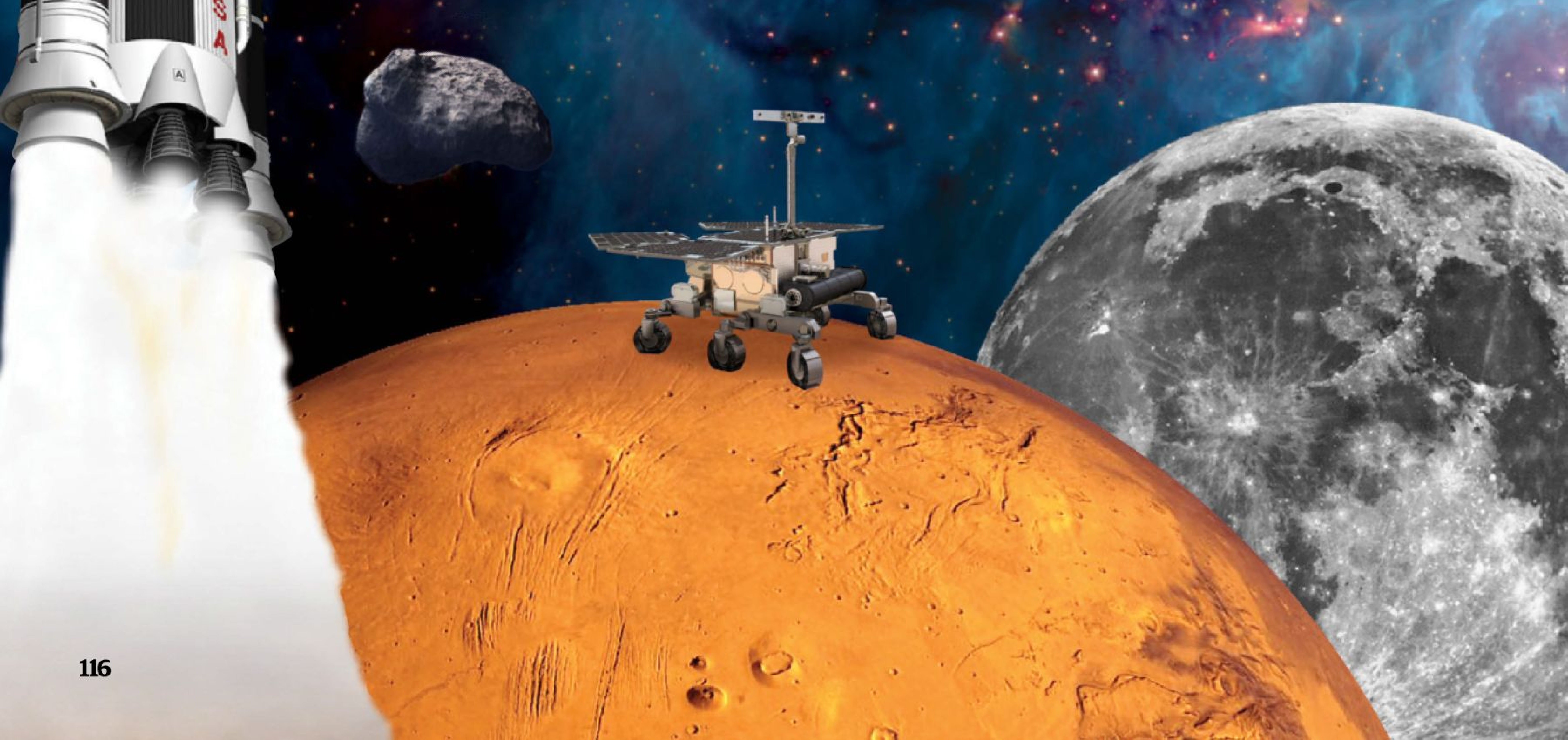
20 TOP SPACE QUESTIONS ANSWERED

Our array of experts from across the world answer some of the most intriguing questions about the cosmos

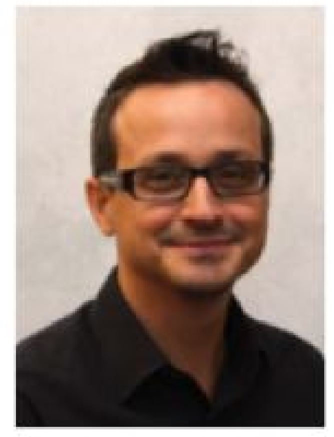
The universe has always astounded us, from our early ancestors gazing up at the sky to the multitude of modern mysteries that keep us baffled. One thing that has pervaded all of these ages, however, is our continual desire to question the cosmos around us. Why are there so many binary stars? How many different types of planet could there be? How big can a star get?

And of course, with every passing year we send more and more missions into space to further our knowledge, but many of these carry with them an immense burden to answer questions we just don't know the answers to. Just what exactly are we hoping Curiosity finds on Mars? Will we ever be able to get clear images of exoplanets? What might NASA's next big project be?

Thankfully, we've gathered together a host of experts to answer these very questions for you, or at least provide the best information we've got so far from the people doing the research to seek such answers. So come with us as we take a look at 20 fascinating cosmic questions, from exploration to astronomy, and unearth some of the hidden secrets of the universe.



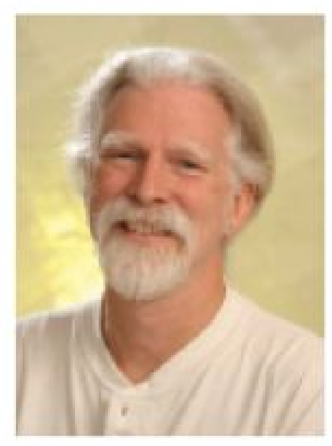
The experts



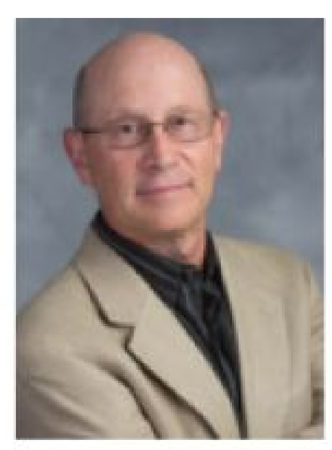
Astrophysicist
Dr Dimitris Stamatellos is the Guild Research Fellow of Astrophysics at the Jeremiah Horrocks Institute at the University of Central Lancashire, Preston, UK.

Space exploration expert
Patrick Troutman is a NASA futurology expert. He can often be found lecturing, writing and talking about the challenges of future human space exploration.

Astrobiologist
Dr Jennifer Eigenbrode is a leading NASA biochemist and geologist. She is currently working on the Curiosity rover's Science Analysis at Mars (SAM) instrument.



Exoplanet spotter
Dr Steve Howell is one of NASA's leading exoplanet experts. He is heavily involved in analysing the multitude of data returned from the Kepler mission.



Senior astronomer
Dr Mark Reid works at the Harvard-Smithsonian Center for Astrophysics. His research interests include black holes, active galactic nuclei, galactic structure and star formation.

Senior mission analyst
Dr Markus Landgraf is working on the Gaia and LISA Pathfinder missions at the ESA. He co-ordinates both astrophysics and fundamental physics mission analysis.

New Horizons scientist
Dr Harold Weaver is a research professor at The John Hopkins University Applied Physics Laboratory. He is currently the project scientist on NASA's New Horizons mission.

Science Editor
Jonathan O'Callaghan is one of our resident experts on **All About Space** magazine. He has a keen interest in astrophysics and a broad knowledge of space exploration.

1. What happens when a giant star meets a smaller star?

Dimitris Stamatellos

"The star formation process is efficient in the sense that it produces stars with masses from a few times the mass of Jupiter up to a few hundred solar masses.

"In a stellar cluster there are many low-mass stars and fewer higher-mass stars. If a giant star (like the Sun) meets a small-mass star (like an M-dwarf or a brown dwarf) then they may end up as a binary system, moving along together and rotating around each other, provided that they have a close interaction, meaning that they come within a few tens/hundreds of astronomical units from each other.

"Even for high-density stellar clusters, those that contain a large number of stars per unit volume, the probability of having such close interactions is relatively small. Collisions between stars in clusters are even more rare (for a globular cluster this is expected to happen once every 10,000 years). If this unlikely event happens, for example in the centre of a cluster, then the smaller star will in effect be swallowed by the larger star with some energy being released during the impact."

In very rare instances a small star can be swallowed by a much larger star

It's almost a certainty that Earth will be struck by a large asteroid again some time in the far future

2. What is the Earth's most likely fate?

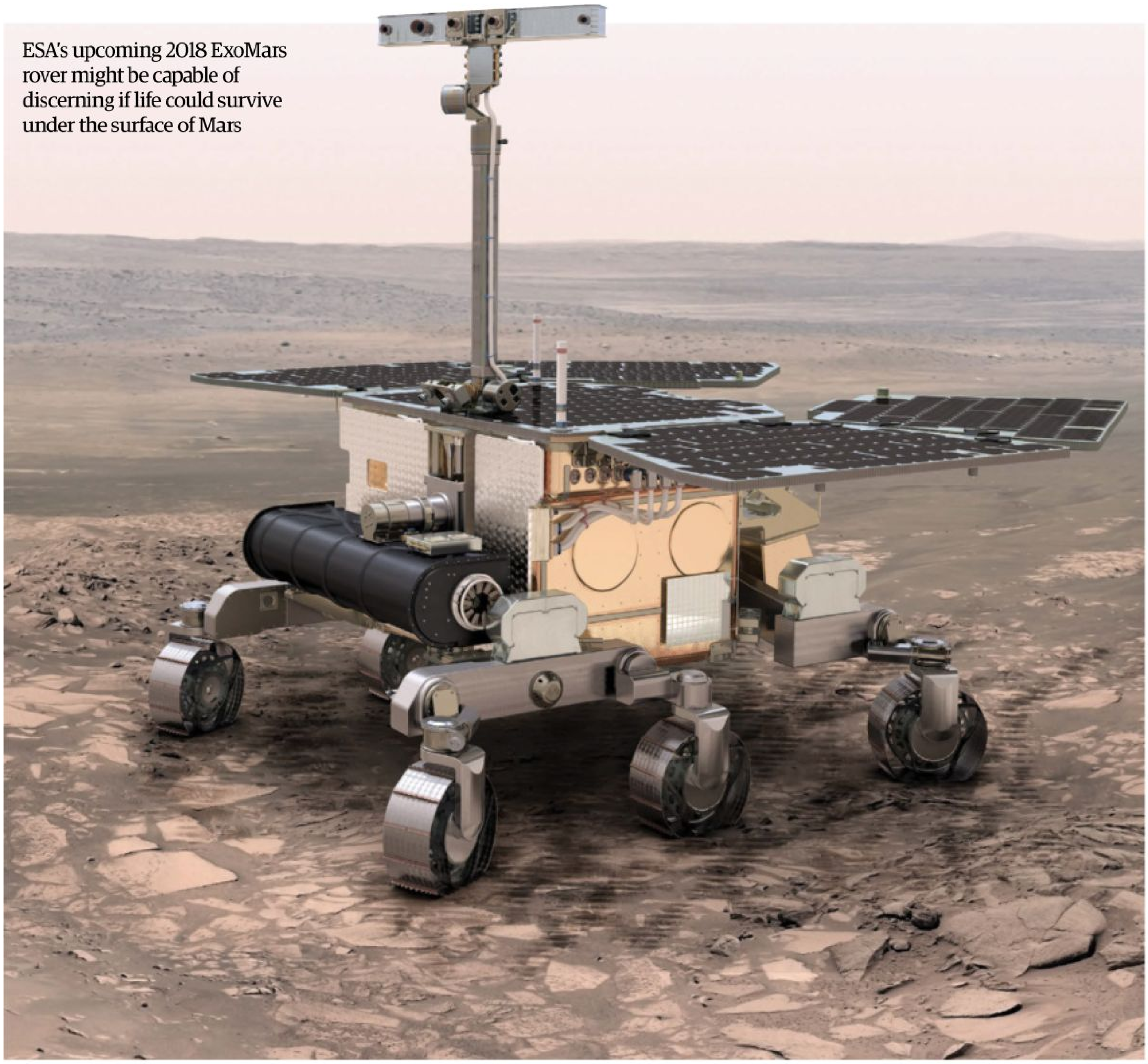
Patrick Troutman

"I'd say the most likely fate for Earth as we know it will come from within. Whether it is a nuclear war, climate catastrophe or collapse of civilisation, one only needs to look at history to see where the future may go. That's why I believe humanity should establish a second biosphere to safeguard civilisation, culture and technology from our mistakes, sort of like seed banks.

"Those man-made collapses would still yield the most life-friendly planet in the Solar System. We have a long time until the Sun turns into a red giant and our oceans boil away. Hopefully we will be out of the Solar System by then. There is always the Jovian system that might be more habitable as the Sun gets bigger.

"Long before the Sun starts to die, Earth will be impacted by a large asteroid or comet, perhaps at the same scale of the impact event 65 million years ago. But life even survived then, and Earth returned to a habitable state. Again, if we had a second biosphere, human civilisation could return to Earth once it was habitable.

"The one fate that worries me most is a small black hole wandering into the Solar System. Would we see it coming? Would it take out Earth, our Moon and Mars? Would we be here blissfully enjoying our existence one moment and then sucked into nothingness the next?"



ESA's upcoming 2018 ExoMars rover might be capable of discerning if life could survive under the surface of Mars

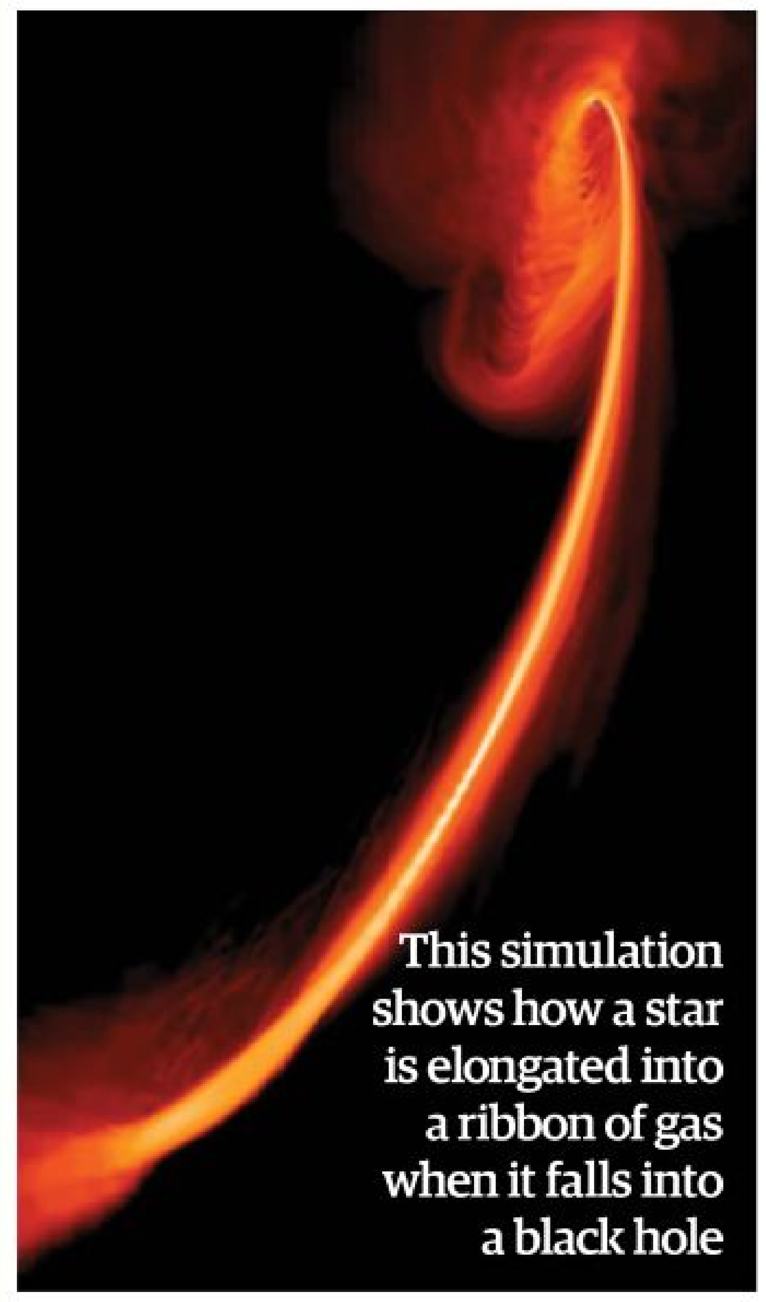
3. Where are we most likely to find signs of alien life in the Solar System?

Jennifer Eigenbrode

"Astrobiologists regard Mars, Titan, Europa and Enceladus as possible habitable places in our Solar System. However, I think the best place for us to search for signs of alien life is in the rocks of Mars that are protected from the ionising radiation currently bombarding the surface. Finding signatures of ancient extraterrestrial microbial life and establishing confidence in that finding will largely depend on the quality of the preserved record. Radiation can seriously alter ancient biosignature records, especially organics, but to what extent and how remains elusive. The reality is that any chemical and physical alteration can complicate and lower our confidence in interpreting signs of ancient life. The same is true for interpreting ancient terrestrial biosignatures.

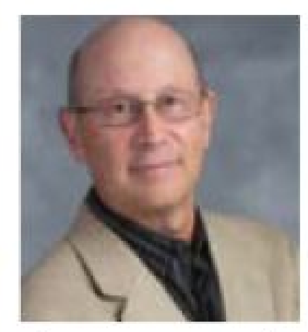
"On Earth, life is ubiquitous – we find life in nearly every extreme environment. This tells us that microbes are incredibly adaptive. However, microbes don't always flourish in extreme environments. We find more and diverse life where nutrients, food and energy sources are plentiful. On Mars, I think it's fair to assume that if life ever existed there, it would be very adaptive too. Over the aeons, life may have learned to cope or even utilise ionising radiation by moving to shielded environments, such as the subsurface, and evolving biochemistry to repair damage to cells. In any case, the ionising radiation makes the top metre or so of surface rocks an extreme environment. If microbes adapted to living in these subsurface rocks, they might flourish if there was a way for nutrients to circulate in the rocks. Perhaps the ExoMars mission will discover clues to the modern habitability of this more protected subsurface environment and if life is there."

"I think the best place for us to search for signs of alien life is in the rocks of Mars"



This simulation shows how a star is elongated into a ribbon of gas when it falls into a black hole

4. What would happen if you fell into a black hole?



Mark Reid

"That depends on the mass of the black hole. Black holes come in two size ranges: 'stellar mass holes' of 3 to 30 times the mass of the Sun and 'supermassive holes' of roughly 1 million to 1 billion solar masses.

"If one were to fall into a stellar mass black hole, the difference in gravity from one's head to foot would be roughly a million 'gs' (the force of gravity on Earth); enough to tear one apart. This was the basic idea behind a Larry Niven sci-fi story called *Neutron Star*.

"However, falling into a supermassive black hole would be an interesting experience. Even though the hole is much more massive than a stellar mass hole, the radius of the hole is much larger also. So, the 'g-forces' across one's body would be insignificant. One could cross the event horizon, and even though light can't escape, it can come inward making for a dazzling show. But, after falling for some hours (depending on the mass and size of the supermassive hole), one would approach the singularity and likely be destroyed."

5. Should we send humans to Mars, an asteroid or back to the Moon?

Patrick Troutman

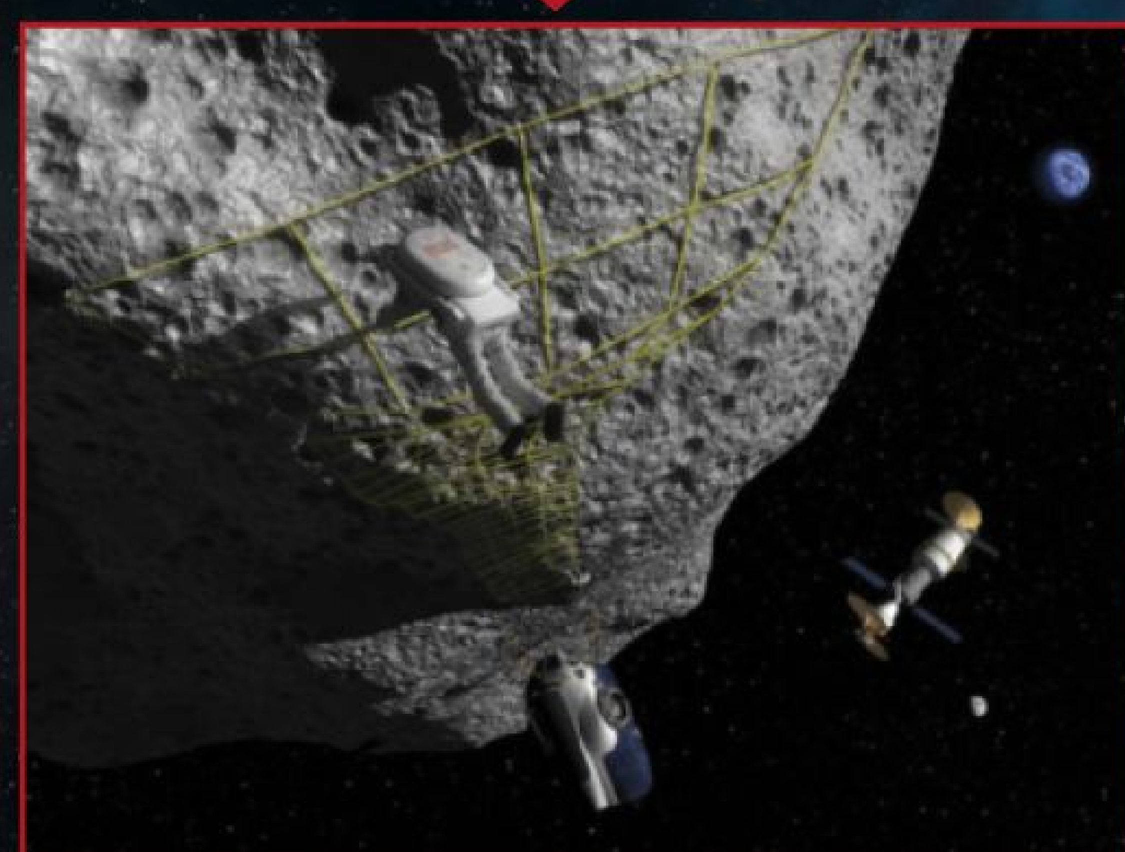
"I'll address science return and mission feasibility, but science is only one reason why we explore, and mission infeasibility sometimes is a reason to explore! There is no right answer as to why we explore, and everyone bases their opinion on their value system and experience. I believe that humans should expand the human sphere of influence beyond Earth in order to further knowledge, enhance our quality of life and assure humanity's survival. So my long-term perspective is about eventually establishing a second biosphere for humanity, so if something bad happens to one, humanity keeps on going."

Resources on the Moon

"The Moon is four days away and contains a vast abundance of resources that we can utilise to break the supply chain with Earth. We need to do that in order to establish an eventual second biosphere. While we are there we can explore its intriguing surface to help understand the formation and evolution of the Earth-Moon system, along with the bombardment history of the Solar System. That's good science. We can also set up telescopes to scan the heavens to new depths. That's good science and perhaps an early warning system for unknown asteroids and comets. Is sending humans to the Moon feasible? Technically, yes. If the world decided that a sustainable Moon base were the next logical step and we pooled our resources to make it happen, then it would."

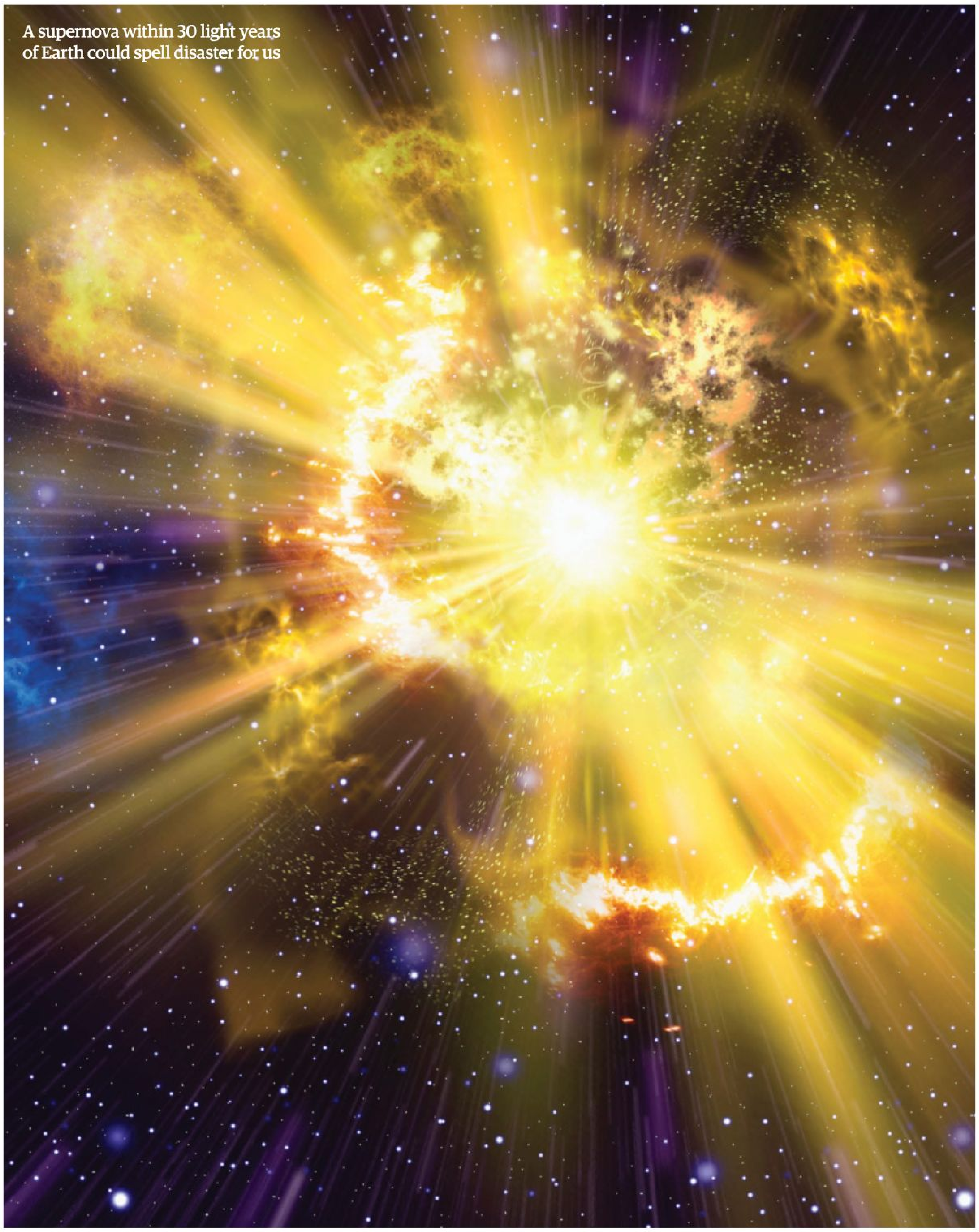
Life on Mars

"Mars is all about life. Life that once existed, life that might exist now, and life – human life – that will be there in future. Science needs to be done on Mars so we can understand how to enable human life there. Most of that science can be done with robots; some could be done much faster if humans were there, but at a significant cost. Affordability of a human Mars mission is our greatest challenge. We can solve the radiation problem by going underground. The entry, descent and landing of large payloads may be more challenging, but smaller human scale entry systems coupled with advances in propulsion may allow us to engineer a solution. The optimal situation may be to send humans to Mars orbit for a decade before attempting to land on the surface, using tele-operated robots to extend the arms and legs of humans so that Mars can be thoroughly explored before humans touch the surface."



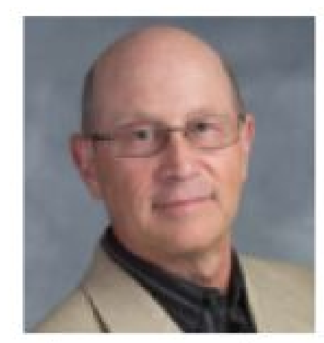
Stopping asteroids

"One way to assure life is to avoid death! Yes, asteroids could contain vast resources that could enable a space-faring society. Yes, they could contain organic compounds that were created during the birth of the Solar System. But what drives me is the fact that asteroids have a history of raining down on Earth. The asteroid that exploded over Russia a year ago was a shot across the bow. The world needs to wake up. We need a global effort to find and track asteroids down to 30 metres (100 feet). It should be our priority. Then we need to develop planetary defence capabilities. These investments are within our budgets and require no major leaps in technology. It doesn't matter if the next impact is in ten or 100 years. The dinosaurs didn't have a space programme. We do. What is our excuse?"



A supernova within 30 light years of Earth could spell disaster for us

6. How close would a supernova have to be to destroy life on Earth?



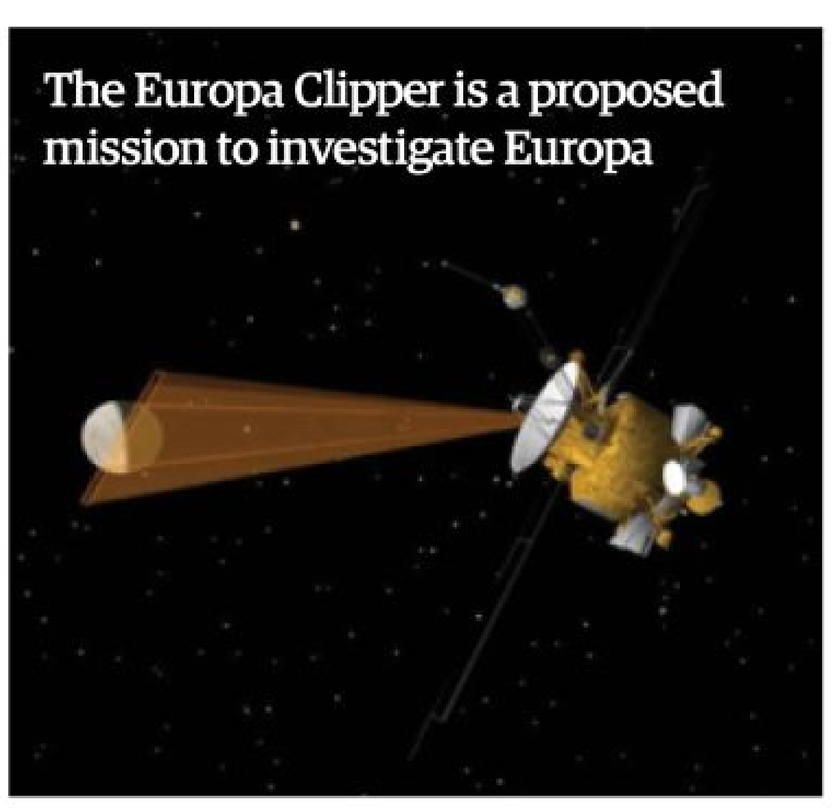
Mark Reid

"The last supernova seen with the human eye was documented by Johannes Kepler in 1604. That was about 20,000 light years away. And while it shone brighter than any star and was visible in daylight, it caused no issues on Earth.

"However, were a supernova to go off within about 30 light years of us, that would lead to major effects on Earth, possibly mass extinctions.

X-rays and more energetic gamma rays from the supernova could destroy the ozone layer. It also could ionise nitrogen and oxygen in the atmosphere, leading to the formation of large amounts of smog-like nitrous oxide in the atmosphere.

"Supernovae happen about once every 100 years in the Milky Way. But the Milky Way is a big place. Given that, and the fact that the Sun is near the outskirts of the Milky Way where few stars massive enough to become supernovae are born, having a supernova within 30 light years of the Sun should, on average, happen only once in every 100 million years."



The Europa Clipper is a proposed mission to investigate Europa

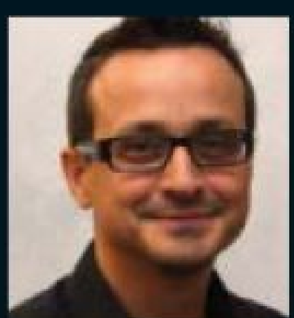
7. What will NASA's next big flagship project be?

Harold Weaver

"According to NASA's current plans, the next flagship mission will be the Mars Science Rover, which is scheduled for a launch in 2020. A flagship mission to Europa has also long been a goal of NASA, as recommended by the last two Decadal Surveys (conducted under the auspices of the National Research Council, at NASA's request). However, the Europa mission hasn't gained much traction because of the severe budget constraints [NASA has been operating under] during the last few years, and it is anticipated to continue for the next few years."

"A flagship mission to Europa has long been a goal of NASA"

8. What is the largest we think a star could be?



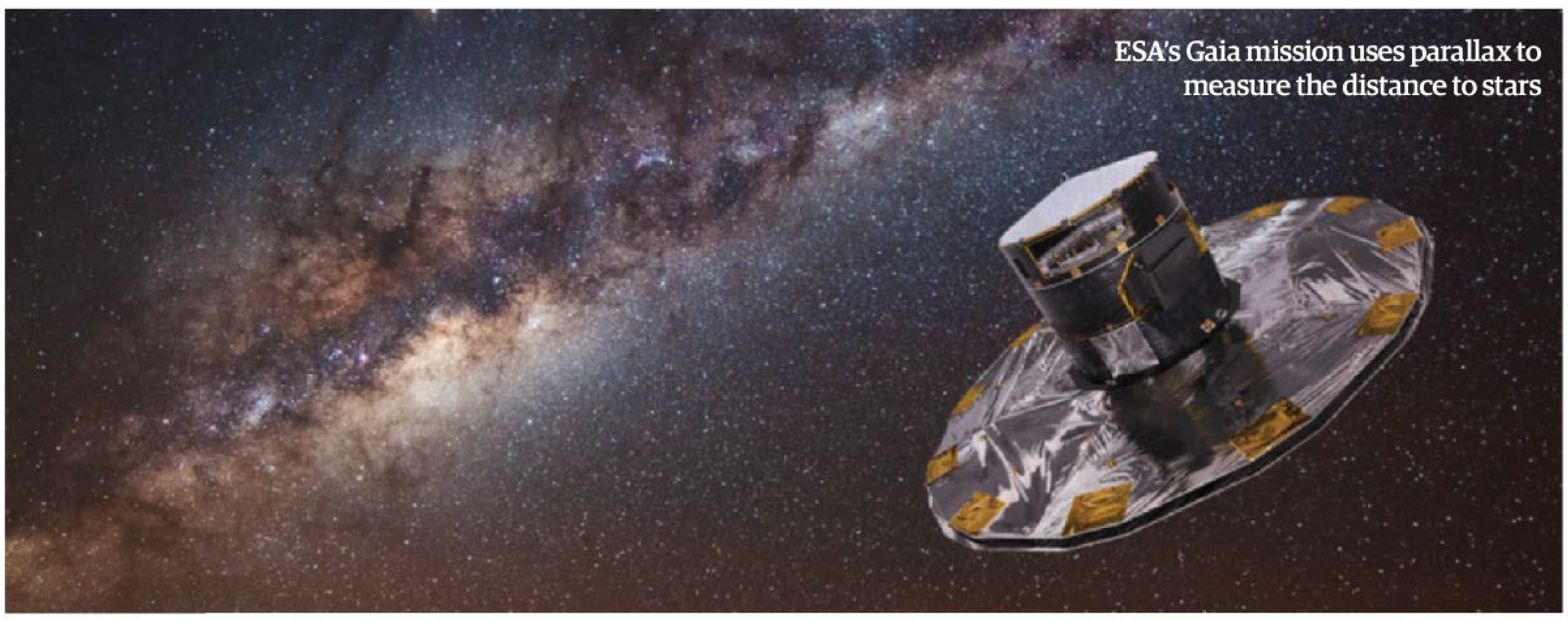
Dimitris Stamatellos

"A star forms when an interstellar cloud of gas and dust collapses under the influence of its own gravity. A newly born star initially has low mass and grows by accreting infalling gas from the cloud. The accretion of material onto the star results in radiating a large amount of energy. The pressure from this radiation pushes the infalling gas away and if it is large enough it can halt the accretion onto the star. If one assumes spherical accretion onto the star, namely gas accumulating onto the star more or less from all directions, then the theoretical upper limit for the stellar mass is around 20 times the mass of the Sun.

"However, there are observations of stars that are a few hundred times more massive than the Sun; the most massive star observed so far is R136a1 which has 260 times the mass of Sun. How can these stellar masses be attained? The presence of discs around newly formed stars is the answer. The growth of mass of the star can continue by accreting gas flowing inwards in the disc, whereas the radiation can escape in other directions. Therefore, the largest stars can be up to a few hundred times more massive than the Sun."

The largest star we've found so far is 260 times the mass of the Sun

9. Are we expecting to find new types of planet?



ESA's Gaia mission uses parallax to measure the distance to stars

10. How do we measure the distance to celestial objects?

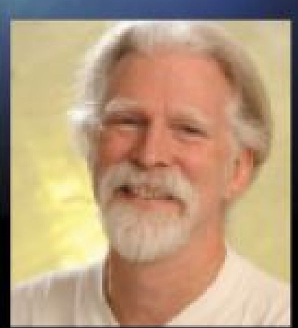
Markus Landgraf

"There are many methods to do this. Let me cite parallax, because we use it in our Gaia mission. For nearby (and not-so-nearby) stars we can exploit the fact that their position in the sky depends on our position as an observer. Much like near objects appear to move in front of background objects when you as an observer move, say driving by a bunch of people in front of a landscape.

"In astrometry we can use the fact that we move with the Earth around the Sun, so our observation position relative to the Sun changes by 2 AU (about 300 million kilometres or 185 million miles) in six months. A star that moves by 1 second of arc (equal to 1/3,600 of a degree) due to the change in our position by 1 AU (the Earth-Sun distance) has a distance of 1 parsec (parallax second). One parsec is equal to 3.26156 light years, which is the distance light travels in 3.26156 years and is equal to 30.9 trillion kilometres (19.2 trillion miles). With Gaia we can basically determine the distance of half of the Milky Way stars using this method.

"For more distant objects, like other galaxies, we use 'standard candles'. Those are variable stars, the absolute brightness of which is correlated with the period of the variation. Knowing the variation, we can derive the absolute brightness. Knowing the absolute brightness and the apparent, measured brightness we can determine the distance. Even further objects, like quasars, are measured by looking at the redshift due to the cosmic expansion. The redshift is directly correlated to the distance as discovered by Edwin Hubble."

There could be a host of new types of planet just waiting to be found in the universe



Steve Howell

"NASA's Kepler mission was launched five years ago and has revolutionised our view of exoplanets, finding planets of all sizes and compositions. The most numerous size of exoplanet seems to be between two to four times the radius of Earth, a planet size we do not have in our Solar System. Therefore we know little about this type of planet, how it forms and what it's made of.

"Other planets discovered have sizes larger than Earth with the density of styrofoam or in the case of two small planets just slightly larger than Earth orbiting the same star but with densities a factor of eight apart. There is even a disintegrating exoplanet, orbiting close to its host star and being evaporated. Discovery is forever dawning, so I'd be amiss to say we will not find new types of exoplanets."

> "The Kepler mission has revolutionised our view of exoplanets, finding planets of all sizes and compositions"

It's thought that half of all stars in the universe could be part of binary systems

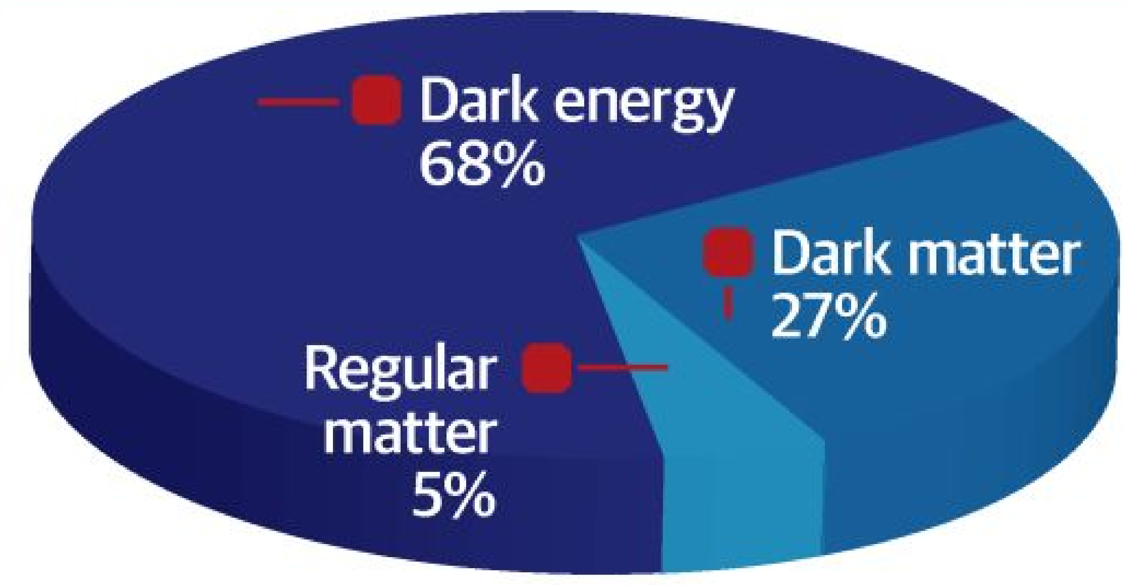
11. Why are binary stars so common?

Dimitris Stamatellos

"It is believed that maybe up to 50% of all stars are in binary systems, with many researchers suggesting that an even higher percentage of stars are born as binaries.

"The high percentage of binary stars is closely linked to the way stars form. It is well established that most stars form in clusters rather than isolated. In the dense parts of clusters such stars could pair up, forming binary stars. Another way that binaries can form is by the breaking up of discs around newly formed stars. These discs are a natural result of the star formation process due to the initial rotation of the interstellar cloud that collapses to form a star. A disc increases in mass as more material from the cloud falls onto it and can become unstable, or in other words it becomes too heavy to be maintained and fragments, breaking up into stars.

"If fragmentation happens quickly after the first star has formed then the two stars may end up having similar masses. If it happens later on, the result will be a binary with two stars with unequal masses. The formation of more multiple star systems (triples, quadruples and so on) is also possible and quite common. The study of binaries is important as their properties contain information about how stars form."



12. What is one of the strangest things in the universe we don't understand?

Markus Landgraf

"In my opinion that would be dark energy. Currently we know that the cosmic expansion is accelerating due to some unseen energy, but no other effect or detection of this energy has been observed or made in an experiment. And the strangest: it makes up the vast majority of our universe. According to the standard model of cosmology, which was confirmed by the ESA Planck mission, the universe is made of 68% dark energy, 27% dark matter, 5% regular matter. So, we can see and explore only 5% of what is out there."

A heavy-lift rocket like NASA's upcoming Space Launch System will be vital for sending humans to the Moon, Mars and beyond

13. How important are heavy-lift rockets for space travel?

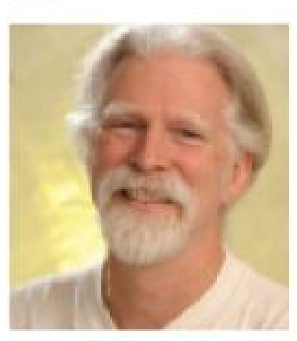
Patrick Troutman

"That sort of depends what you want to do at whatever place you want to go to beyond Earth orbit. If budgets were not a constraining factor, you would simultaneously build the biggest rocket technology would allow, megawatt class in-space propulsions systems for cargo pre-deployment, nuclear thermal in-space stages for crew transport, long duration in-space habitats and capable destination systems to make the people as productive and self-sufficient as possible for any mission at the chosen destination.

"If you are talking about going to Mars, a heavy-lift rocket simplifies the mission architecture by allowing more systems to be integrated into mission vehicles that enable contingencies to be mitigated without having to rely on another launch or rendezvous. Even with a heavy-lift launch vehicle, there are too many launches (six to 12) required to pull off a conjunction class mission with about a 500 day surface stay if everything is thrown away after each mission. Decreasing the size of the launch vehicle just multiplies the problem. However, I know of no place on Earth where budgets are not a factor!

"The development of a new launch vehicle (especially a heavy-lift rocket) is one of the most expensive aspects of space exploration, and the operational costs of heavy lift facilities and vehicles are covered just by the missions that use them, leaving a small portion of the total budget to develop everything else. If the mission that truly required a heavy-lift vehicle were 30 years away, it would make sense to leverage existing launch vehicles to extend our reach into cislunar space, build up our long duration experience on the ISS from months to years and take the funding that would have been spent on heavy-lift and invest that in all the other capabilities humans will need to thrive in space. Then ten years before humans proceed to that new challenging destination, begin development of a heavy-lift vehicle that could leverage all the other technology developments before it."

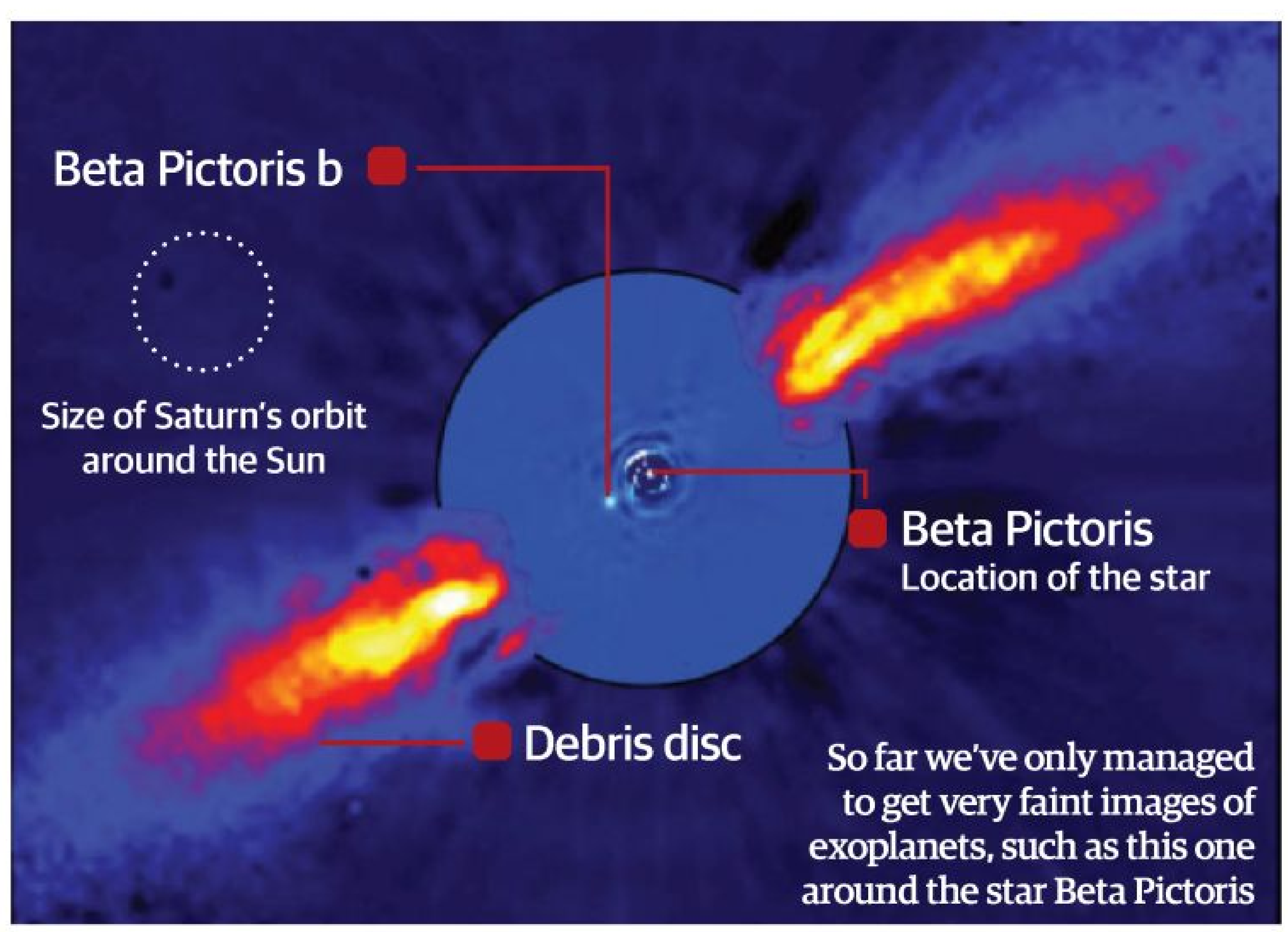
14. What telescope would we need to get clear images of exoplanets?



Steve Howell

"Exoplanets have already been directly imaged orbiting the stars Fomalhaut and Beta Pictoris, as well as three exoplanets orbiting HR 8799. These planets are large Jupiter-sized bodies orbiting far from their host star and are observed with special instruments called coronagraphs that are used to block the star light while leaving the planets visible.

"In order to get a clear image of a possible habitable exoplanet, such as an Earth analogue, the observation would need to be able to resolve the star from the planet and deal with the very large contrast in light between the two. To get a feel for these two difficult tasks, get a bright torch (flashlight) and a small marble. Have a friend stand across a room from you, hold the marble against the torch, and shine the light directly into your eyes. Can you see the marble? Small, close-in exoplanets orbit very near, in angle, to their stars and shine only very dimly by reflected light. Thus, just building a big telescope alone will not allow the observation. Astronomers are working to make special telescopes such as the James Webb Space Telescope and special instruments (star shades and vortex coronagraphs) that can be placed in space, above the disrupting effects of our atmosphere, in the hope of obtaining a direct image and measurement of an Earth-like planet, perhaps revealing signatures of life."



So far we've only managed to get very faint images of exoplanets, such as this one around the star Beta Pictoris

It might seem cluttered, but the chances of things colliding in Earth orbit are actually very slim

15. Why don't objects collide often in Earth orbit?

Jonathan O'Callaghan

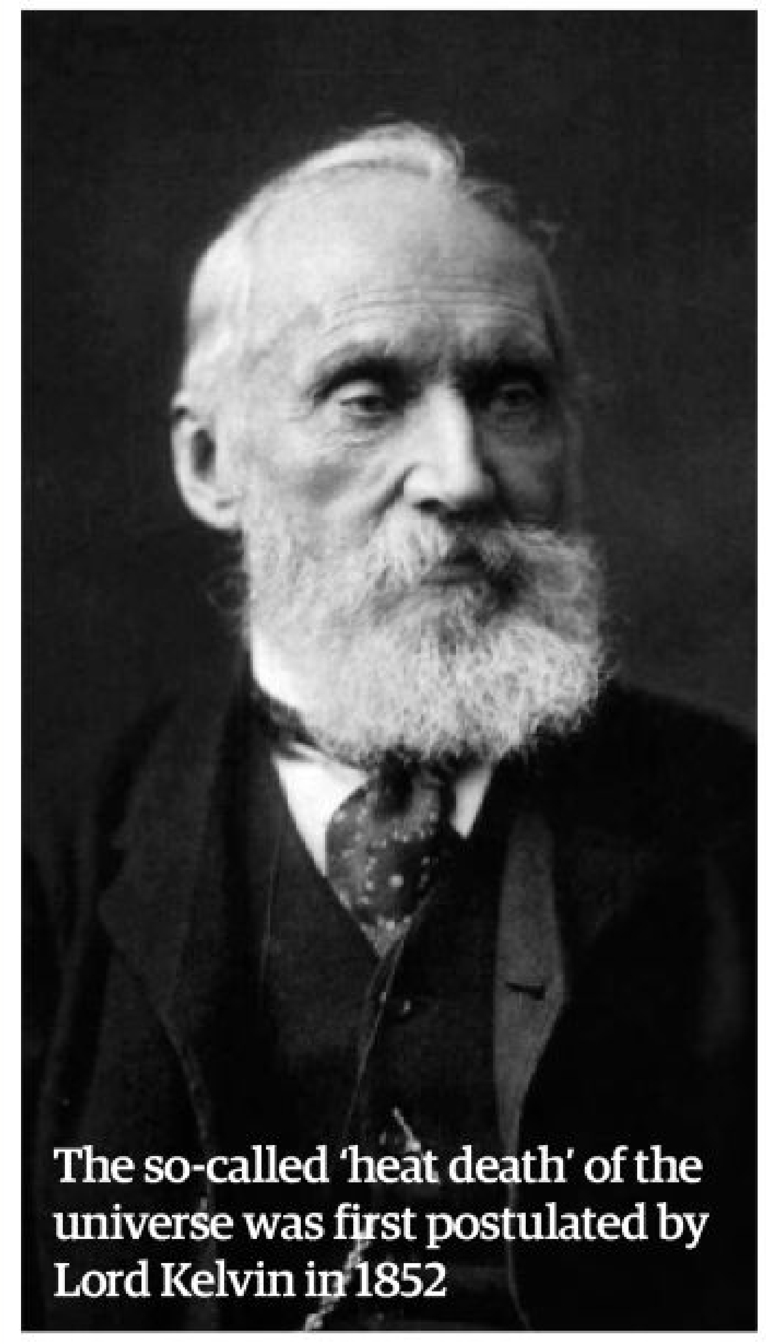
"The distance between things in orbit is vast, and Earth orbit is a huge place. Put simply, the chances of any two things colliding are very slim, despite there being thousands of active satellites in orbit and many more pieces of smaller space debris, because there is just so much space between everything.

"However, another reason is that most of our man-made satellites travel in similar orbital bands at similar speeds within those bands. This means they're moving in the same direction at specific heights, sort of like an imaginary conveyor belt moving around Earth. There's not much chance of one satellite catching up to another and, even then, the chances of a collision are low.

"The only major risk to something like the ISS, which is 370 kilometres (230 miles) high in low Earth orbit, would be if someone launched a satellite into orbit in the opposite direction to the ISS at the same height, which isn't really possible thanks to orbital mechanics; most things (aside from satellites in polar orbits) move the same way Earth rotates to get a speed boost at launch.

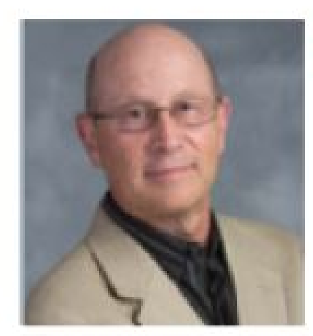
"Collisions are not unprecedented, though. In 2009 an active US satellite collided with a defunct Russian satellite, destroying both and creating thousands of pieces of debris larger than ten centimetres (four inches). Thankfully a lot of debris of this sort will be pulled into Earth's atmosphere and burn up on re-entry, although some debris does remain a threat."

"The chances of two things colliding are very slim"



The so-called 'heat death' of the universe was first postulated by Lord Kelvin in 1852

16. Will all the stars in the universe eventually die out?



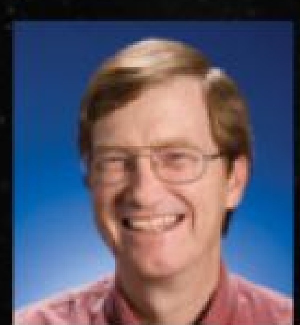
Mark Reid

"The Sun has been around for roughly 5 billion years and will live another 5 billion years. Then it will go out in a blaze of glory as a giant red star, possibly engulfing the Earth, before exhausting its nuclear fuel and becoming a dimming ember.

"Other stars that are only a tenth of the mass of the Sun, shine dimmer than the Sun, but do so for a very long time... sometimes up to trillions of years.

"But even as stars burn out over time, others are continually born from gas and dust inside galaxies like the Milky Way. Ultimately, however, all that material will be used up, and in roughly 100 trillion years there will be no material to form new stars. Then the universe will grow dark."

17. What can we expect from New Horizons when it reaches Pluto?



Harold Weaver

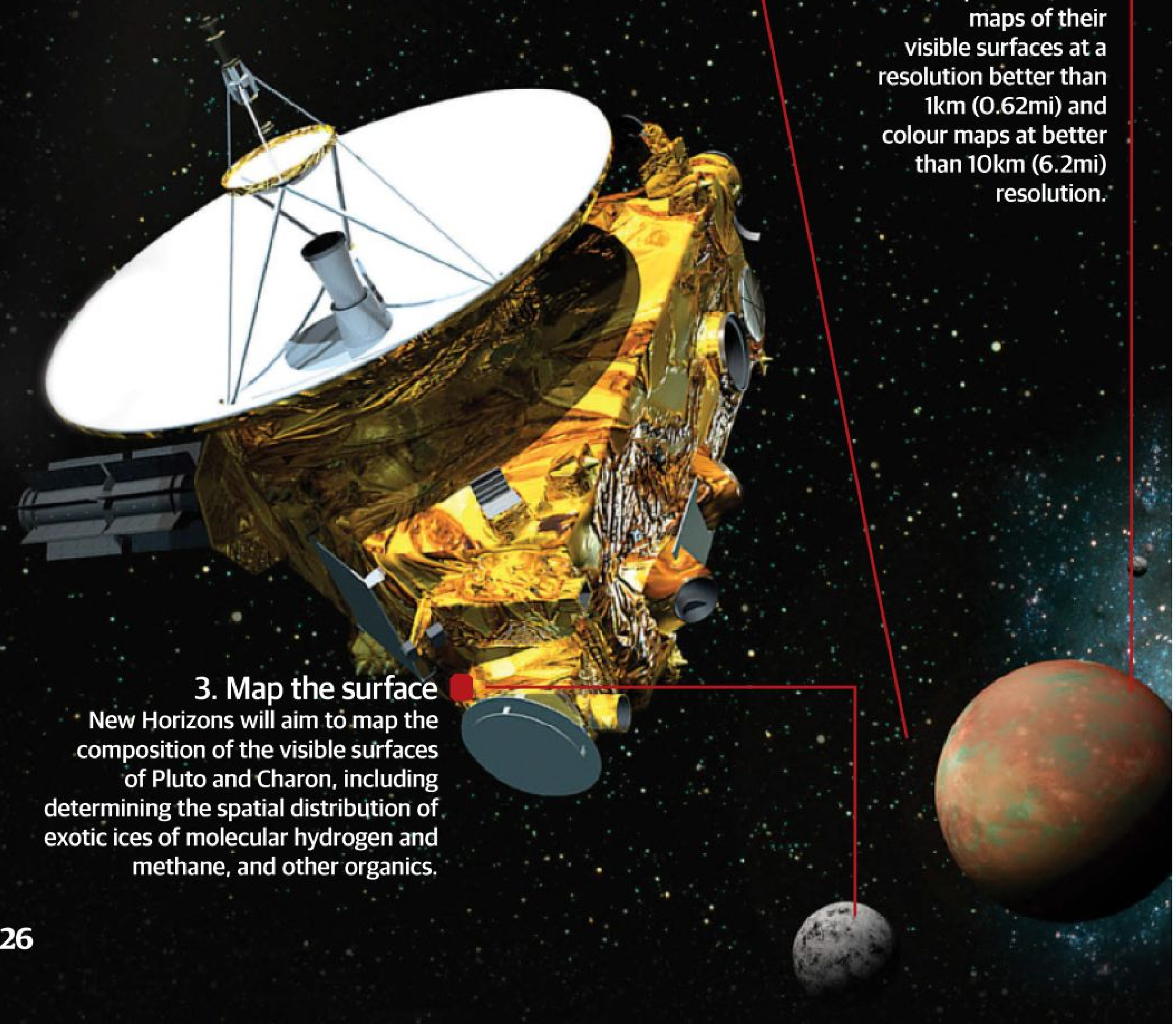
"The New Horizons mission will revolutionise our understanding of the Kuiper belt by providing the first in situ exploration of objects beyond Neptune's orbit after it arrives at Pluto in July 2015. New Horizons carries a sophisticated suite of seven scientific instruments, including panchromatic and colour imagers, ultraviolet and infrared spectral imagers, a radio science package, plasma and charged particle sensors and a dust counting experiment. Using these instruments, New Horizons will explore a new class of Solar System objects, the dwarf planets, which have exotic volatiles on their surfaces, escaping atmospheres and satellite systems."

3 key science objectives for New Horizons

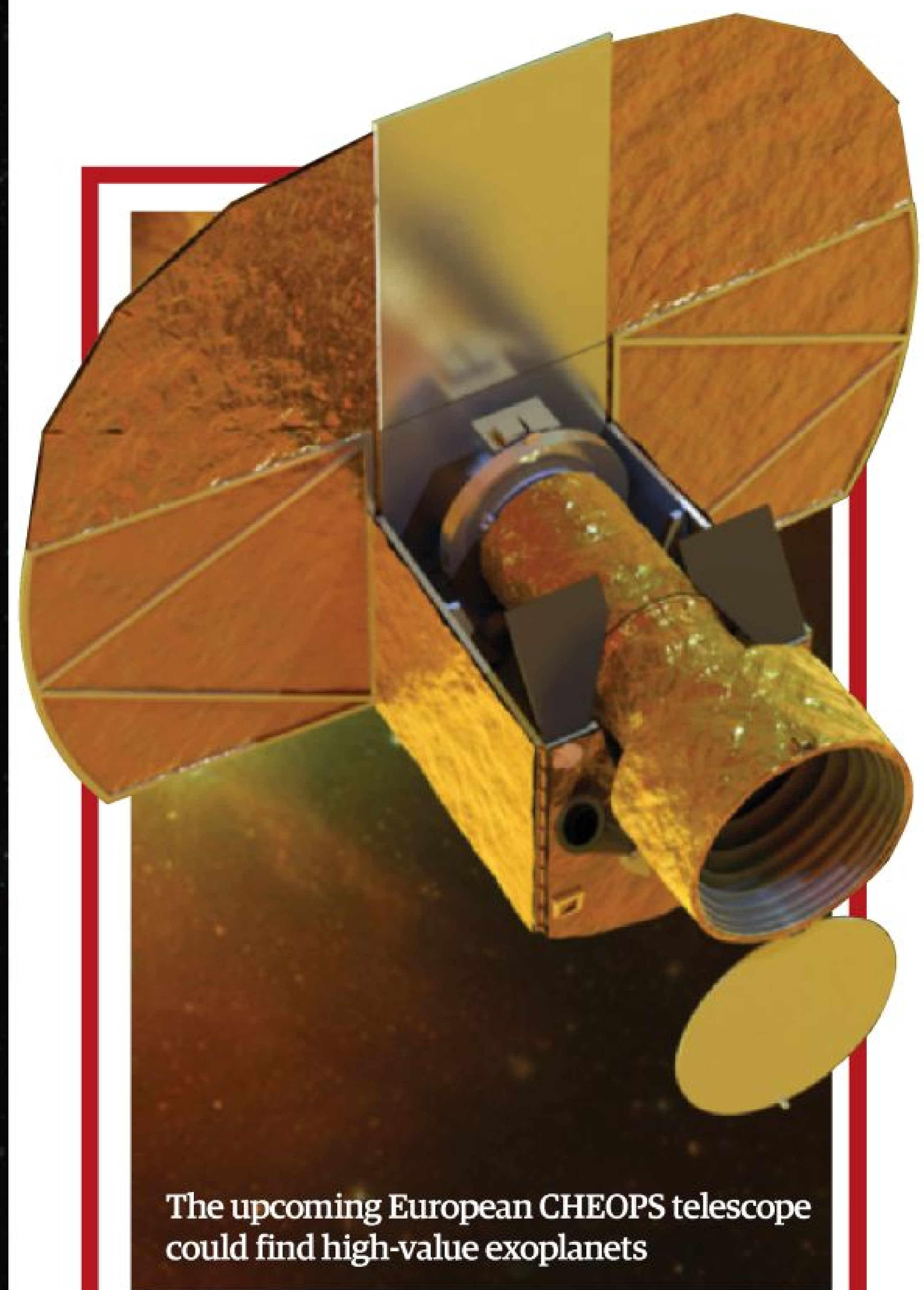
New Horizons launched on 19 January 2006 on a mission to become the first spacecraft to study the Plutonian system

1. Measure the atmosphere
To characterise the atmosphere of Pluto, New Horizons will measure the abundances of molecular nitrogen, carbon monoxide, methane and argon. It will also determine the atmosphere's temperature versus height above the surface, and it will measure the effect of the escaping atmosphere on the impinging solar wind particles.

2. Geology and morphology
New Horizons will characterise the global geology and morphology of Pluto and its moon Charon by obtaining panchromatic maps of their visible surfaces at a resolution better than 1km (0.62mi) and colour maps at better than 10km (6.2mi) resolution.

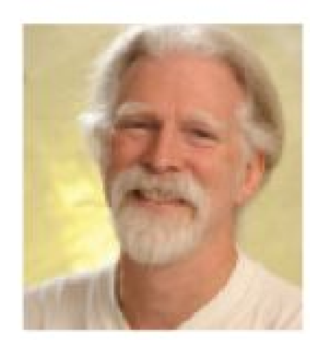


3. Map the surface
New Horizons will aim to map the composition of the visible surfaces of Pluto and Charon, including determining the spatial distribution of exotic ices of molecular hydrogen and methane, and other organics.



The upcoming European CHEOPS telescope could find high-value exoplanets

18. What breakthroughs in planet hunting can we look forward to?



Steve Howell

"The next step in planet hunting is characterisation. We now know that planets are common in our galaxy and orbit most stars. Astronomers are moving from searching for planets to finding what are termed 'high-value' planets and studying them in great detail.

"High-value planets are either ones that orbit bright stars such as 55 Cancri or Kepler 21 or planets that orbit very nearby stars such as GJ 1214. The reason these types of planet are valuable lies in the ability to perform follow-up observations, that is using large telescopes on the ground and in space to determine the planet mass and density as to allow study of its atmosphere. These parameters tell us if the planet is rocky like the Earth or gaseous like Jupiter. These additional observations can also tell us if the planet has an atmosphere and if that atmosphere might contain life-bearing molecules such as water or oxygen. Near-term space missions such as K2, TESS (Transiting Exoplanet Survey Satellite), and CHEOPS (CHaracterising ExOPlanets Satellite) will find such high-value star-planet combinations, thereby providing targets to follow up with current telescopes and planned future telescopes such as the James Webb Space Telescope (JWST)."

This incredible mosaic image from the Cassini spacecraft shows Saturn's rings backlit by the Sun

19. How did Saturn's rings form?

Jonathan O'Callaghan

"At the moment, no one is quite sure. Since their discovery by astronomer Galileo Galilei over 400 years ago in 1610, scientists have been trying to work out exactly how these magnificent rings came to be, the most extensive ring system that we know of around any planet. The rings are made up of ice and rock with billions of pieces ranging in size from a grain of sand to a house. The rings are hundreds of thousands of kilometres wide, but only a few tens to hundreds of metres thick. Exactly how they formed, though, remains somewhat of a mystery to scientists and astronomers.

"One leading theory is that the rings are the remnants of one or several moons that once orbited Saturn. It is possible that a moon could have been torn apart by a combination of Saturn's gravity and the influence of other moons, causing its debris to be scattered around the planet in a ring. The rings may also have formed, or perhaps been added to, by passing comets and asteroids being pulled in by Saturn's enormous gravity and, in turn, also being broken apart into many smaller fragments, entering an orbit around Saturn that flattened over vast periods of time into the thin but incredibly wide rings we see today."

20. What are we hoping Curiosity finds on Mars?

Jennifer Eigenbrode

"We are hoping that Curiosity finds organic molecules in the sedimentary rocks at Mars's Gale Crater. Organic molecules hold clues to both their source and the processes that have changed them over geological time. Often, they are turned into gas and lost due to oxidation. This is a common occurrence on Earth. On Mars, the ionising radiation may accelerate organic breakdown and loss, but this process is poorly understood because we have no terrestrial analogue for the radiation environment on Mars.

"All of life produces organic molecules for their cellular structures and as waste products. Life also uses organics in the environment as a food source. The presence of organic molecules would support a habitat if life existed. The presence of certain molecules may even tell us if life was the source for the organics, but this type of finding is beyond the scope of Curiosity's objectives. Future missions will specifically search for signatures of ancient life.

"Understanding how organic molecules might be preserved and the processes that break them down in rocks at Gale Crater is a key focus for the mission. Curiosity has the right tools to start our exploration of how the geology and radiation exposure act to preserve and destroy the ancient organic record. This understanding will become a cornerstone for all future astrobiology missions looking for signs of ancient life."

Curiosity is able to use its suite of on-board instruments to analyse the Martian surface

One of Curiosity's key goals is to look for signs of organic molecules at Gale Crater

The power of GRAVITY

It shapes the universe, enables the stars to shine and controls our everyday lives – but how much do we really know about one of the most elusive forces in the universe?

The power of gravity

Throw an apple in the air, catch it and you're seeing the power of gravity at work just as surely as when you look up to the Moon, speeding along its orbit a quarter of a million miles from Earth. This ubiquitous force pervades the universe, emanating from every massive object and influencing anything that comes close enough. The gravity from enormous clusters of galaxies can be felt across hundreds of millions of light years, while on smaller scales the gravitational collapse of gas is what ultimately heats and compresses the cores of stars and enables their nuclear reactions to take place. Yet gravity is curiously elusive on the smallest scales – we cannot measure it as a property of individual particles and its behaviour contradicts much of what we know about the other fundamental forces of the universe.

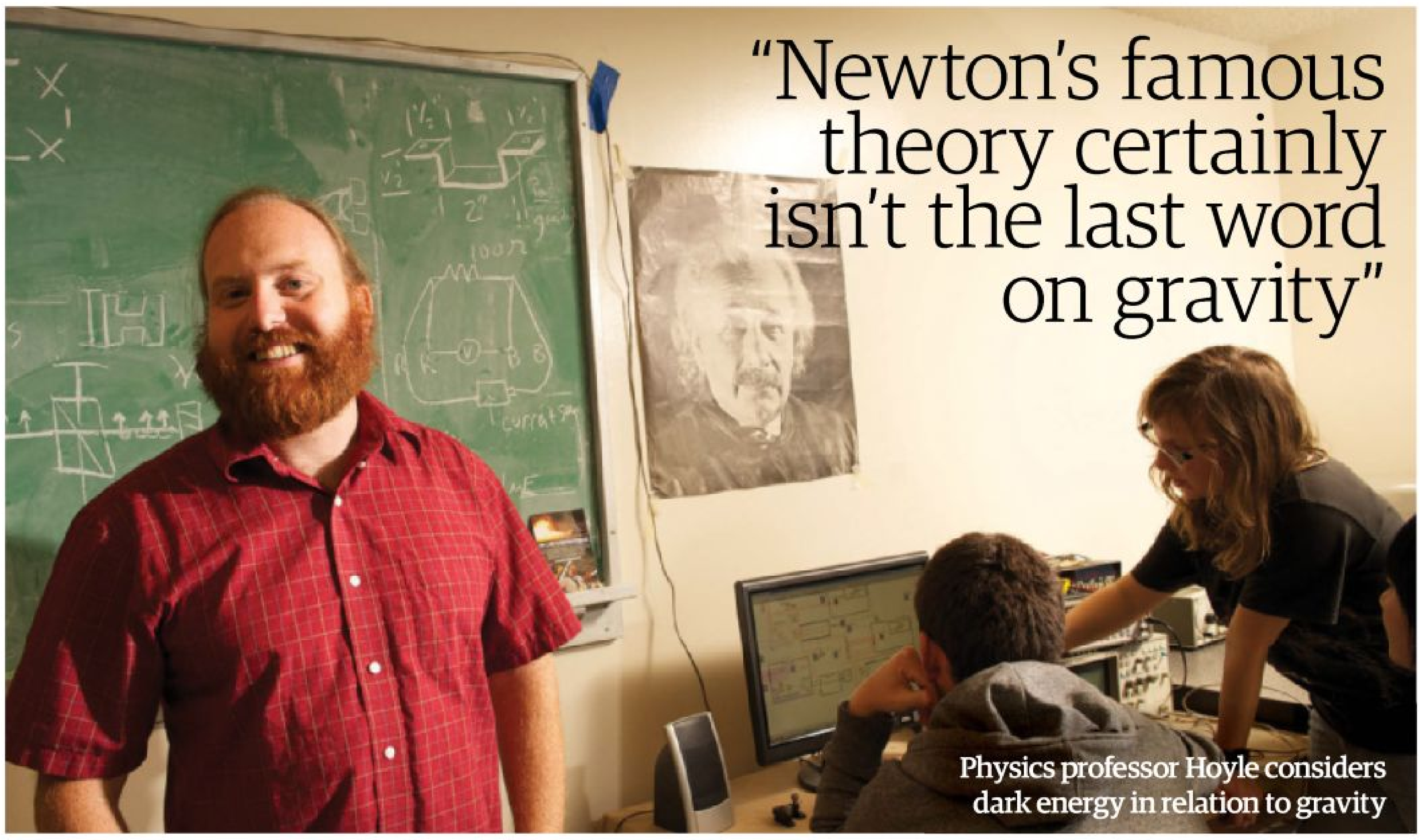
Physicists and astronomers have been struggling to understand gravity ever since the Renaissance. The great Italian scientist Galileo Galilei was one of the first to realise that gravity on Earth affects all objects equally regardless of mass. According to legend, he proved this point in 1589 by dropping balls of different masses off the Leaning Tower of Pisa and showing that they hit the ground at the same time. Almost four centuries later, Apollo 15 commander David Scott demonstrated Galileo's point conclusively by simultaneously dropping a feather and a hammer on the surface of the Moon – they hit the ground at exactly the same time.

It was English physicist Isaac Newton in around 1666, however, who first made the connection between objects falling on the Earth and the behaviour of the Moon and planets in distant space. While German mathematician Johannes Kepler had correctly described the behaviour of planets in their orbits, he had not ventured to suggest the force that might control their behaviour. It was Newton who imagined what might happen if the force that gave objects weight on Earth extended to the Moon and beyond and in 1687 he finally put forward his law of universal gravitation.

"Physicists are always looking for unification and simplification and gravity was one of the first examples of that," explains C.D. Hoyle, professor of Gravitational Physics at California's Humboldt State University. "Newton was able to unify the terrestrial realm, and the way objects fell on the Earth, with the orbits of the planets, which were at the time considered to be a completely separate phenomenon."

As equations go, Newton's law is one of the simpler ones: it describes how the gravitational force depends on the masses involved and the distance between them. As you might expect, the force of gravity gets bigger as either of the masses involved grows larger, but it falls off rapidly with increasing distance (double the distance and the force falls to just a quarter). Despite that, however, it turns out that the acceleration due to gravity at a given distance from an object depends only on that single object's mass. This is how we can say that the acceleration due to gravity at Earth's surface (often written as lower-case 'g'), for instance, is 9.81 metres (32.19 feet) per second squared, without worrying about the mass of the object actually being accelerated. Acceleration falls off only gradually as you get away from Earth's surface – at the altitude of the International Space Station it is still 90 per cent of g.

This star-forming region in the constellation Cygnus has been pinched into an hourglass shape by the newly formed star, S106 IR



Physics professor Hoyle considers dark energy in relation to gravity

G is the universal constant that determines the actual strength of the gravitational force, usually known as the Gravitational Constant. Although measuring acceleration due to gravity is relatively simple, measuring the value of G itself is much more of a challenge. British scientist Henry Cavendish achieved it in 1798 by using an ingenious mechanism called a torsion balance. In this experiment a rotating framework rather like a coat-hanger, with weights hanging on either side, is suspended from a single wire and allowed to twist freely, influenced only by the gravitational attraction between the moving weights and a second pair of larger weights fixed nearby. The moving weights come to a halt when the attractive force between them balances the resistance or torque created by the twisting of the wire.

In most situations, Newtonian gravity still provides a perfectly accurate model for gravitational calculations; it's used without a second thought by engineers calculating the physics of everything from buildings and aircraft to elevators and rockets. Since gravity is simply a force in a constant direction, it's theoretically possible to create artificial gravity in so-called micro-gravity situations such as Earth orbit. Spinning a pair of spacecraft around each other creates a virtual centrifugal force that mimics gravity, as does simple constant acceleration (though this is considerably harder to produce with current rocket engines). The challenges of generating artificial gravity are purely practical rather than theoretical.

However, Newton's famous theory certainly isn't the last word on gravity and in fact during the 19th century astronomers discovered some situations in which it seemed to fail. For example, the elliptical orbit of Mercury changes its orientation, or precesses, over time quicker than Newtonian gravity would seem to suggest. Despite this, the gravitational revolution that came in the early 20th century emerged from a very different direction.

C.D. Hoyle takes up the story: "Newton's theory of gravity worked pretty well for almost 250 years, until Einstein came along. General relativity was born out of the study of light – the consistent speed of light in the universe was a problem whose solution ultimately required a whole new view of gravity."

Einstein's new model of gravity was just one part of his wider theory of general relativity – a model of the nature of space and time that developed organically alongside his investigations of special relativity (the behaviour of bodies moving at speeds close to the speed of light). He realised that space and time are not the fixed properties they appear to be, but instead form a four-dimensional space-time that can be warped in various ways. Special relativity shows how time would slow down for fast-moving objects, while their length in the direction of travel would be compressed. However, in 1911 Einstein realised that a gravitational field is physically equivalent to a state of constant acceleration – in other words if a person were sealed in a rocket with no outside information, they would be unable to conduct an experiment to show whether the rocket was accelerating constantly, or simply sitting on the ground in a gravitational field.

Thinking through the consequences of this, Einstein realised that a gravitational field should bend the path of light rays moving through it, despite the fact that light is massless and therefore immune to Newton's version of gravity. In Einstein's theory, large masses created distortions in space and time (what we experience as gravity) that affect massive and massless objects alike.

Einstein's ideas were controversial at the time and despite his already formidable reputation in the scientific community, they were largely ignored on publication in 1915. They only came to widespread attention in 1919, after British astronomer Arthur Eddington led an expedition to the island of Príncipe off west Africa to observe the Sun during a total solar eclipse. Measuring the positions of stars around the Sun, Eddington found that they did not appear in their normal positions and therefore showed that their light was being deflected as it passed through the Sun's gravitational field. "Einstein did calculations

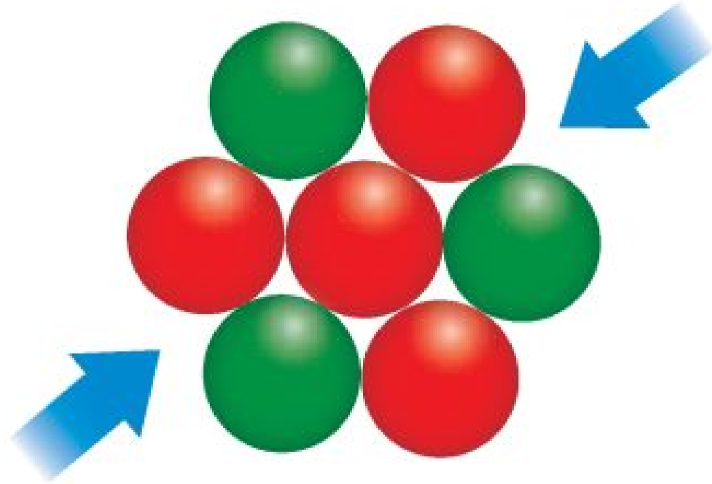
What is it?

According to our current understanding, gravity is a distortion of four-dimensional space-time that makes itself felt as a force acting on objects. While many early scientists assumed it acted instantaneously across huge distances, Einstein showed that gravity could propagate no faster than the speed of light, giving rise to the possibility of gravitational waves (one of the few predictions of general relativity that has not yet been observed, though physicists are certainly looking).

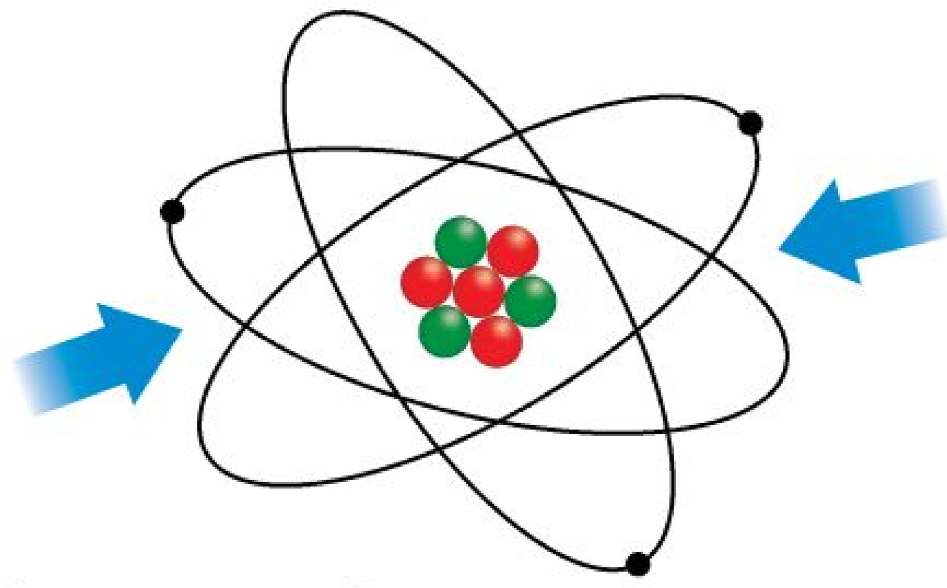
Perhaps the biggest challenge facing modern physics is how to reconcile general relativity, Einstein's description of gravity, with the various quantum field theories that describe nature's other fundamental forces. Gravity appears to be very different, though theoretical physicists hope that it might ultimately prove to be transmitted from one object to another by an exchange of hypothetical messenger particles called gravitons.

Other forces use these messengers (collectively known as gauge bosons), so that if the graviton could be found, it would at least prove that the forces operated by the same broad principles. However, even then there would be major unanswered questions such as why gravity only makes itself felt when large numbers of particles are gathered together and how it makes its presence felt over such enormous distances.

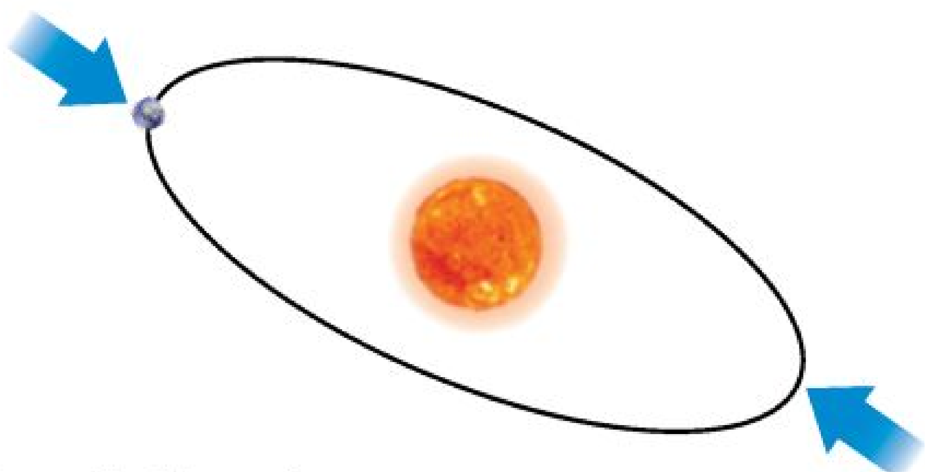
The four forces of nature



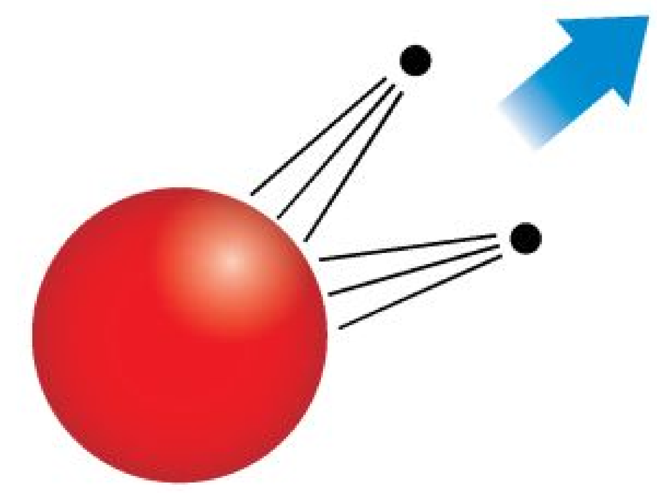
Strong
The strong nuclear force binds particles together on the tiny scale of the atomic nucleus. It affects elementary particles called quarks and combines protons and neutrons together to form nuclei.



Electromagnetic
The electromagnetic force affects particles with electric charges and operates over intermediate scales. It makes itself felt through phenomena such as electricity and is transmitted by photons.

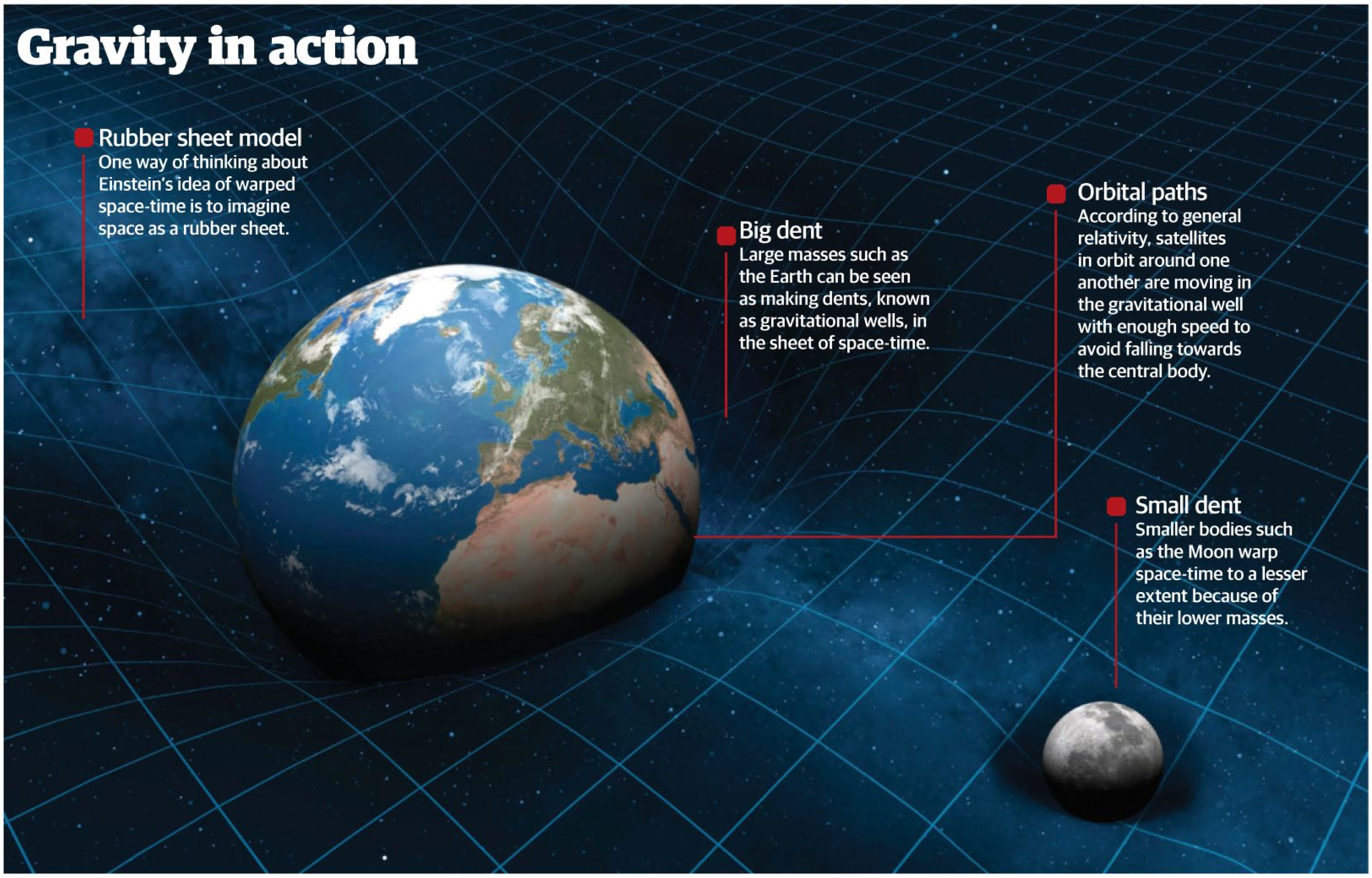


Gravitational
This force is the weakest of all on the subatomic level, but it's felt when matter gathers in bulk and it has an enormous range. It operates by distorting space-time rather than via carrier particles.



Weak
This force operates inside the atomic nucleus and transforms one kind of quark into another. Unusually the weak force is transmitted by three different carrier particles: the W+, W– and Z particles.

Gravity in action

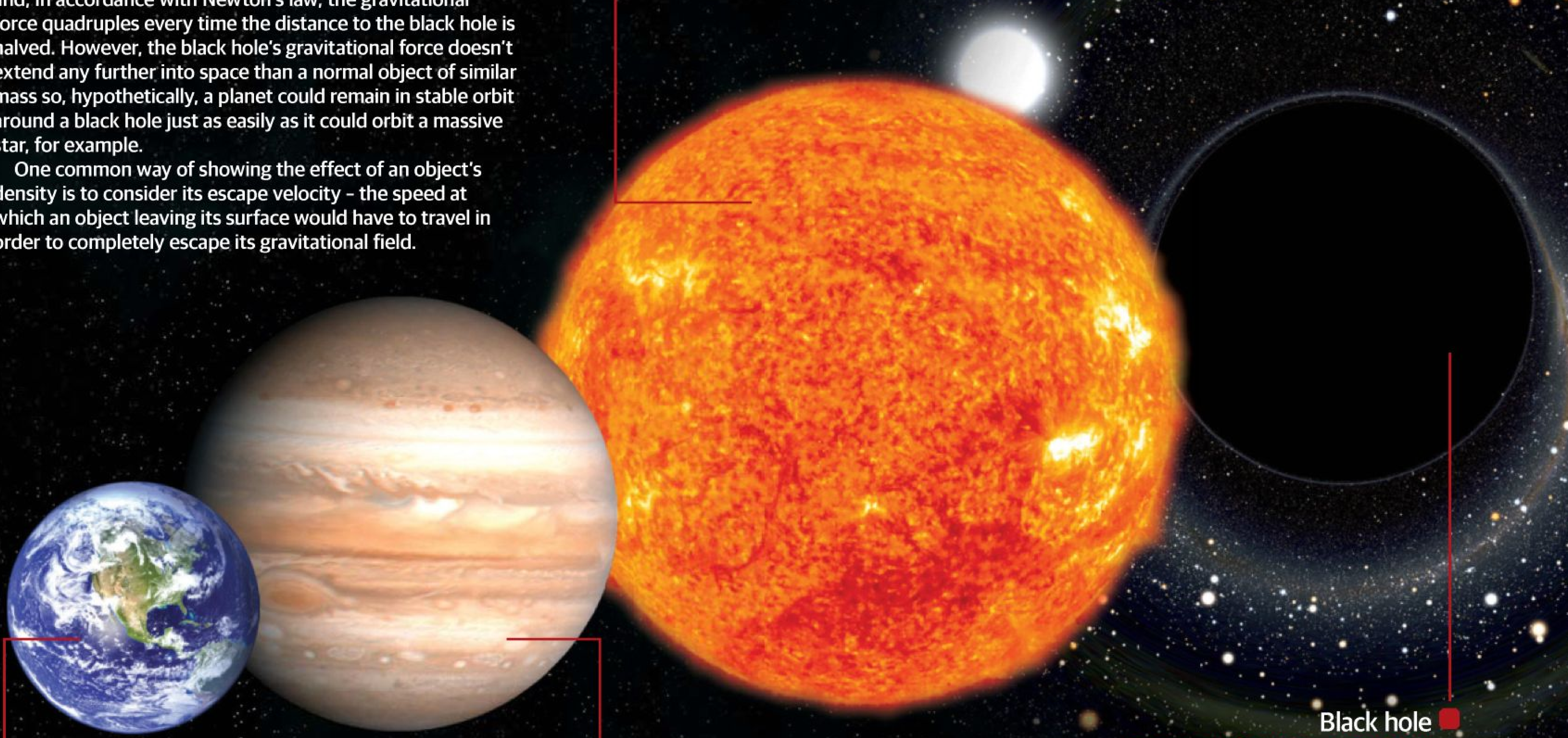


Gravitational strength

Although the gravitational force exerted by any object depends only on its mass and distance, the composition of objects also has a role to play, since the density or concentration of mass governs how close we can get to it.

The most famous examples of extreme gravity are black holes – collapsed stellar cores that concentrate the mass of several Suns in a single point known as a singularity. A black hole's gravity only becomes so huge because its density means that objects can get incredibly close to it and, in accordance with Newton's law, the gravitational force quadruples every time the distance to the black hole is halved. However, the black hole's gravitational force doesn't extend any further into space than a normal object of similar mass so, hypothetically, a planet could remain in stable orbit around a black hole just as easily as it could orbit a massive star, for example.

One common way of showing the effect of an object's density is to consider its escape velocity – the speed at which an object leaving its surface would have to travel in order to completely escape its gravitational field.



The Sun
Escape velocity: 617 kilometres per second
The Sun contains the mass of 333,000 Earths, but its huge size means that escape velocity at its surface is just 55-times Earth's. However, its mass is so great that a speed of more than 42 kilometres per second is needed to escape the Sun starting from Earth's orbit.

Earth
Escape velocity: 11.2 kilometres per second
Any object attempting to leave Earth is slowed down by acceleration due to gravity, but gravity falls off with distance from Earth, so if the object can achieve escape velocity, it can outrun the force and escape Earth's gravity entirely.

Jupiter
Escape velocity: 59.6 kilometres per second
Jupiter has 318-times the mass of Earth, but less than a third of its density, so escape velocity from its cloudtops is only 5.3-times Earth's.

Black hole
Escape velocity: > 300,000 kilometres per second
A black hole may contain the mass of more than a million Earths, compressed to a singularity in space. This means that the escape velocity may be faster than the speed of light (and therefore physically impossible) out to a boundary called the event horizon. This is why nothing can escape from a black hole.

that explained the perihelion precession of Mercury, but it was Arthur Stanley Eddington's observation of this gravitational lensing that really clinched the case," adds Hoyle.

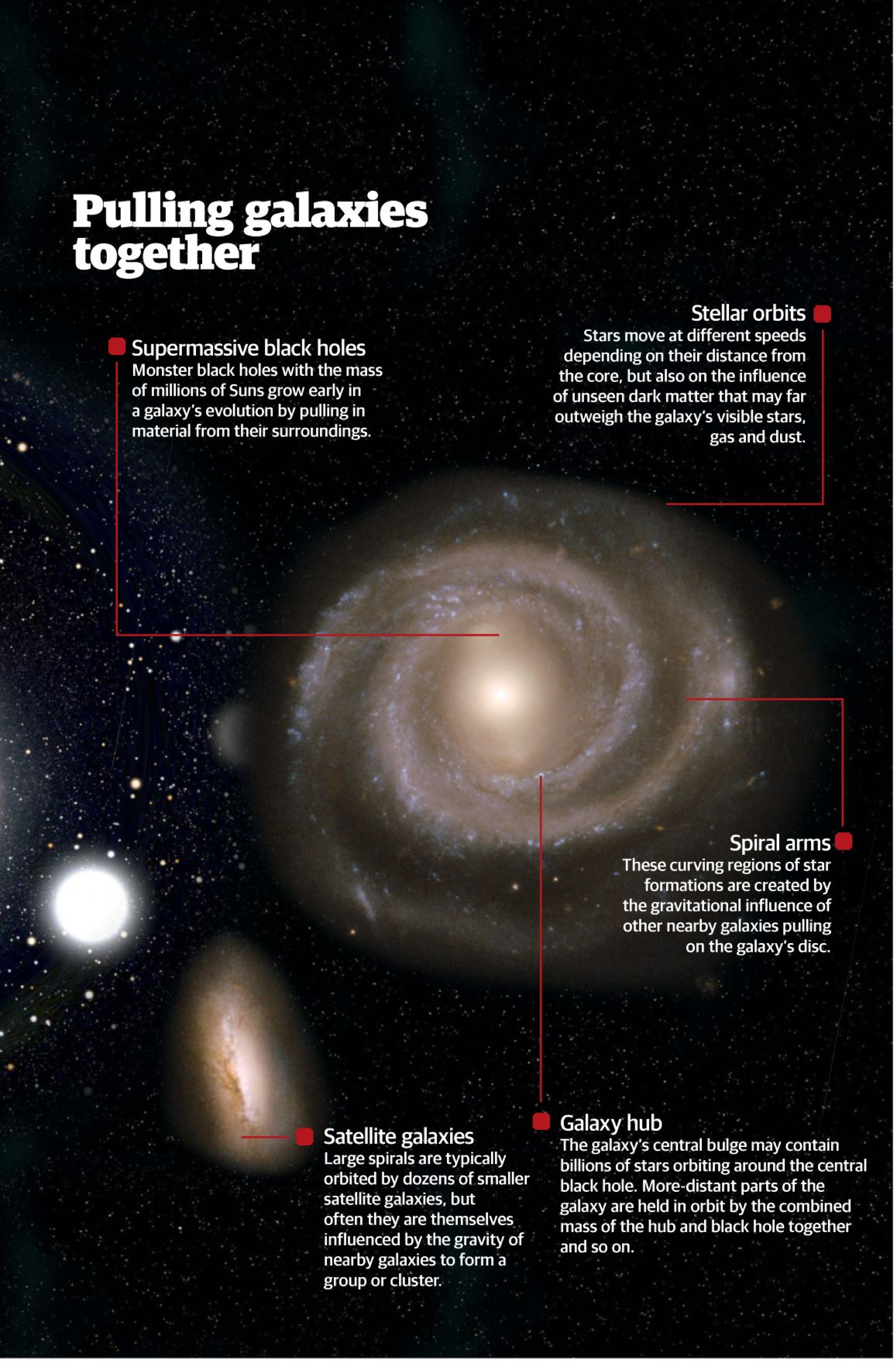
Today astronomers have harnessed this strange effect, known as gravitational lensing, to peer into the depths of the universe. As well as distorting the images of distant objects, lensing can also intensify their light. For example, dense galaxy clusters can warp the light from even more-distant galaxies many billion of light years away. Even extrasolar planets passing across the face of their stars can cause them to brighten momentarily through an effect commonly known as microlensing.

> "Understanding how gravity works at a quantum level could also help solve the mystery of dark energy"

Since Einstein's time, general relativity has been proven correct in a wide range of experiments and it is still widely accepted as an accurate description of the way gravity works on the large scale of galaxies, stars and planets. However, physicists are still concerned about how to reconcile it with other aspects of the universe; gravity is just one of four fundamental forces and the others behave differently.

"A lot of efforts were made early on to unify the new theory of general relativity with electromagnetism," says Hoyle. "In the 1920s Theodor Kaluza and Oskar Klein explained how if you introduced a fifth dimension, you could kind of unify gravity and electromagnetism, though it didn't work out exactly right. People didn't really think about it in mid-20th century, though, when nuclear and particle

Pulling galaxies together



physics were the hot areas of research and it turned out there were these two other forces operating at a subatomic level."

Today, however, particle physicists have good reason to believe that they may eventually come up with a way to explain the three quantum-level forces as aspects of a single superforce, but adding gravity to the mix is perhaps the biggest challenge of all. The first step would simply be to understand how gravity works in the context of the quantum world - a theory of quantum gravity whose behaviour might start to diverge from general relativity at small scales.

"The point is that we live in one universe, so there shouldn't really be two theories needed to explain how it works that are mathematically at odds with each another. Quantum mechanics, for example, does not behave properly around the gravitational singularity of a black hole, whereas general relativity copes with that, no problem," explains Hoyle.

Understanding how gravity works at a quantum level could also help solve the mystery of dark energy - the puzzling phenomenon of the modern universe that seems to be accelerating the expansion of the universe. While some theories of dark energy suggest it is an independent fundamental force, others see it as an intrinsic property of space-time itself, perhaps intimately connected with gravitation. Testing gravity's small-scale properties lies at the heart of

Five gravity myths

1. Astronauts experience zero-gravity in orbit

Astronauts in orbit actually experience almost the same gravity as on Earth. Orbit is a state where an object's straight-line speed is delicately balanced against gravity's tendency to pull it back to Earth. Because the astronauts and spacecraft share this state, they are in constant free-fall and weightless.

2. Weight and mass are the same

Actually, no. An object's mass is a measure of the quantity of material it contains, while its weight is a measure of the force exerted on it by gravity, so it can change depending on the object's location. Properly, mass is measured in kilograms while weight should be measured in Newtons, the standard units of force.

3. Earth's gravity exerts the same force on all objects

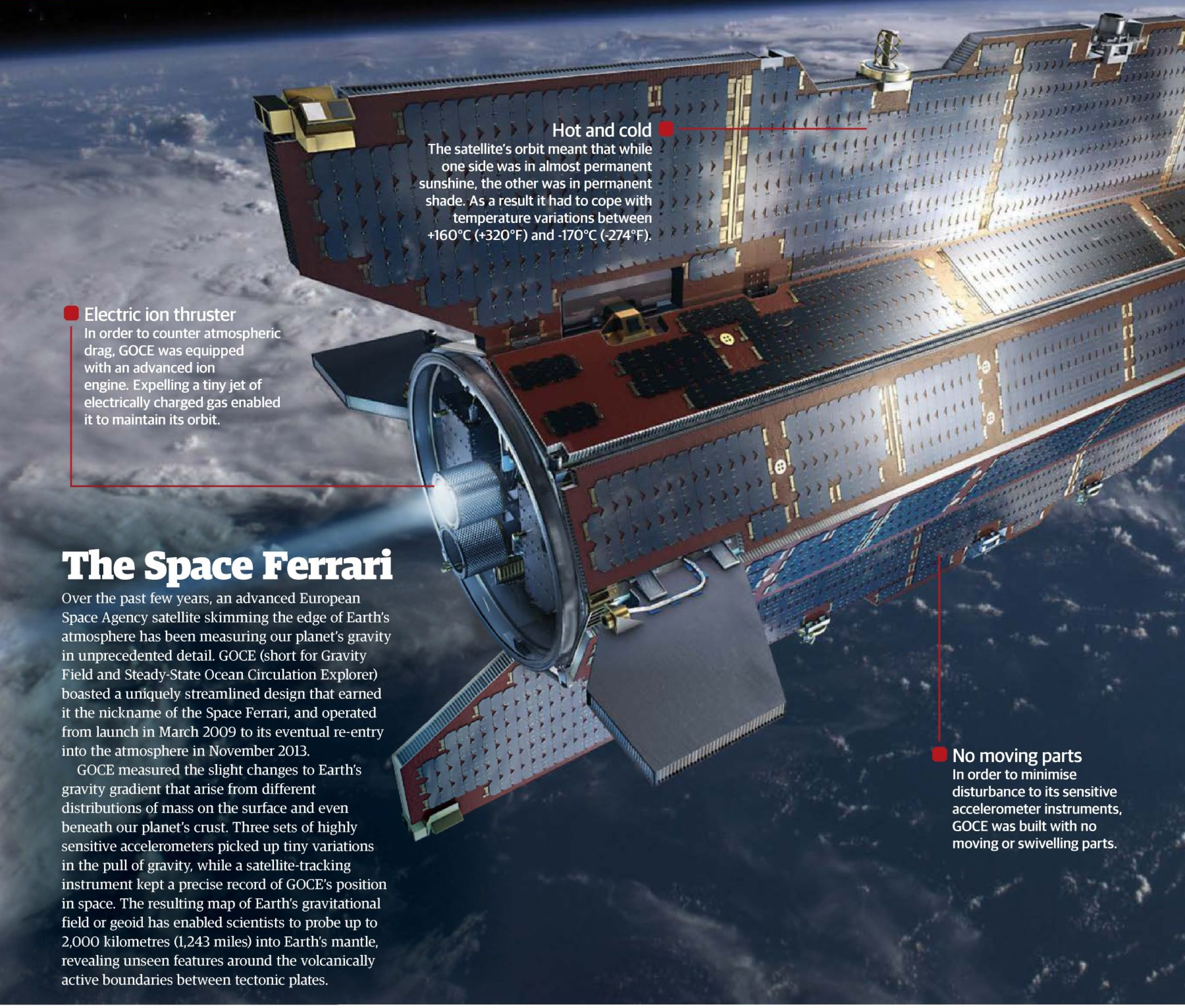
No it doesn't - Newton's law shows that the force depends on the object's mass as well as the Earth's. But heavier objects also require more force to accelerate them, so all objects experience the same acceleration due to gravity.

4. Gravity gets stronger with increased height

No, barring some minor variations, Earth's gravity is at its strongest on the surface of the Earth. It gets weaker with height, as you get further away from the source of the gravity, and also decreases inside the Earth. Here there is less mass pulling you towards the centre and an increasing amount of mass pulling you upwards from overhead.

5. If you could reach the centre of the Earth, you'd be entirely weightless

This one depends on what you mean by weight. There's plenty of gravity at the centre of the Earth, but it would pull at you from all sides and therefore if you could find the perfect centre, it would cancel out.



The Space Ferrari

Over the past few years, an advanced European Space Agency satellite skimming the edge of Earth's atmosphere has been measuring our planet's gravity in unprecedented detail. GOCE (short for Gravity Field and Steady-State Ocean Circulation Explorer) boasted a uniquely streamlined design that earned it the nickname of the Space Ferrari, and operated from launch in March 2009 to its eventual re-entry into the atmosphere in November 2013.

GOCE measured the slight changes to Earth's gravity gradient that arise from different distributions of mass on the surface and even beneath our planet's crust. Three sets of highly sensitive accelerometers picked up tiny variations in the pull of gravity, while a satellite-tracking instrument kept a precise record of GOCE's position in space. The resulting map of Earth's gravitational field or geoid has enabled scientists to probe up to 2,000 kilometres (1,243 miles) into Earth's mantle, revealing unseen features around the volcanically active boundaries between tectonic plates.

Gravity through the ages

1589 Galileo's experiment

Galileo realised that acceleration due to gravity was the same for all objects regardless of mass – reportedly by dropping weights off the Leaning Tower of Pisa.

1609 Kepler's laws

German astronomer Johannes Kepler reveals his laws of planetary motion – describing the properties of any object in orbit around another but not addressing the causes of the motion.

1687 Newton's gravitation

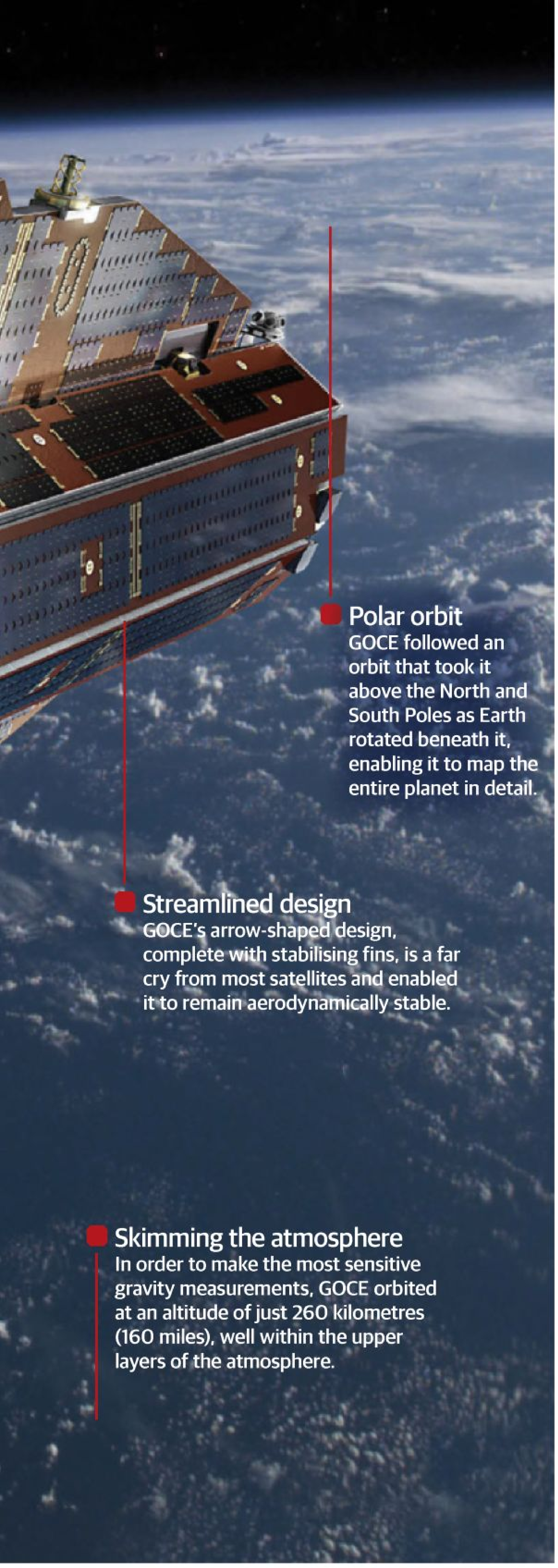
Isaac Newton publishes his great work, the *Principia*, outlining three laws of motion and the law of universal gravitation, showing how Kepler's laws arise from gravity.

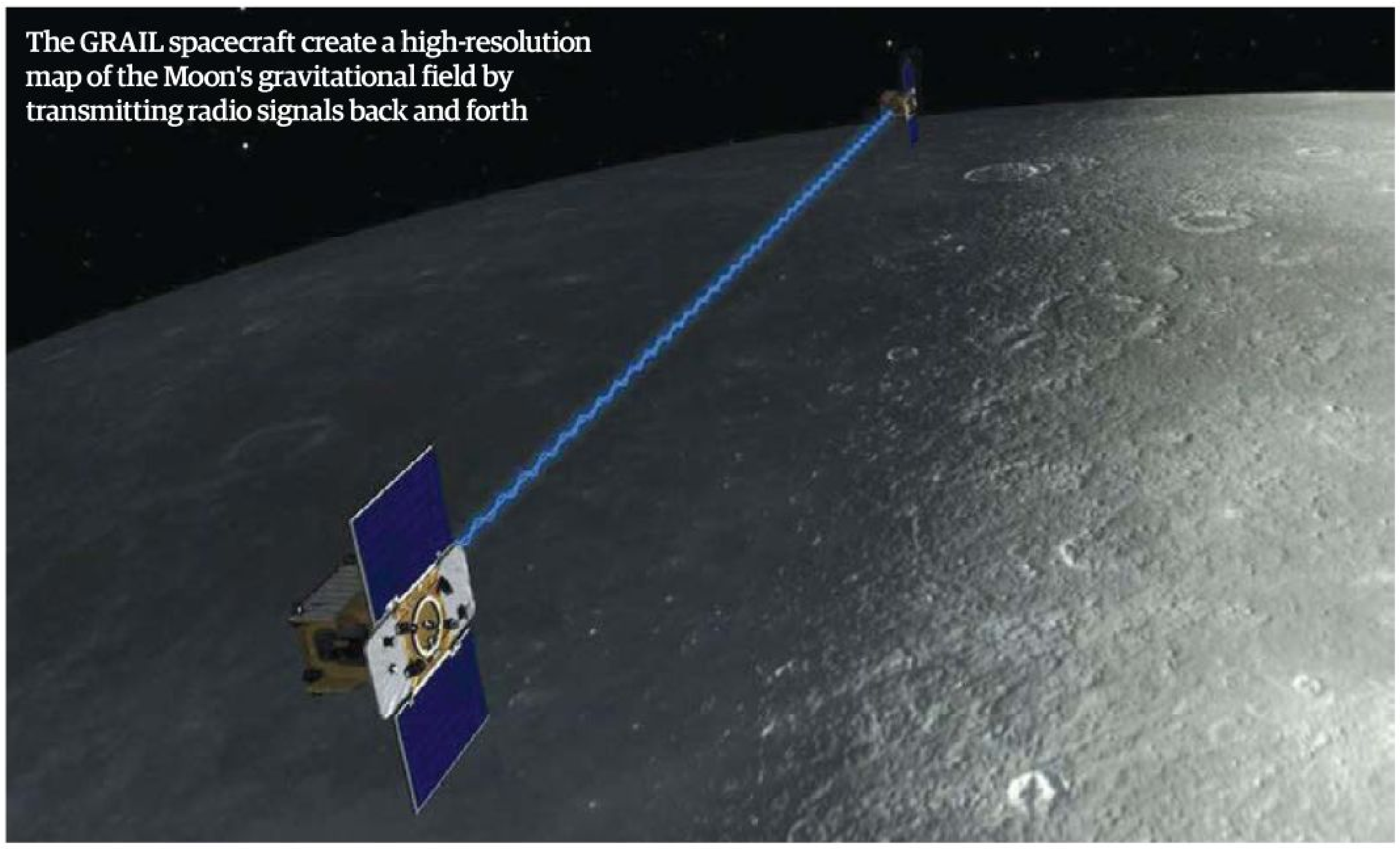
1798 Measuring G

Henry Cavendish uses a torsion pendulum to measure the weight of Earth, measuring the Gravitational Constant in the process.

1846 A new planet

French mathematician Urbain Le Verrier predicts the location of a new planet, Neptune, based on its gravitational disturbance of the orbit of Uranus.




The GRAIL spacecraft create a high-resolution map of the Moon's gravitational field by transmitting radio signals back and forth

"We might be looking at evidence of extra dimensions"

Hoyle's research at Humboldt: "The fact is that there's never been a direct measurement of gravity below the 50-micron scale, so we currently just have to assume it works all the way down to the smallest quantum scales."

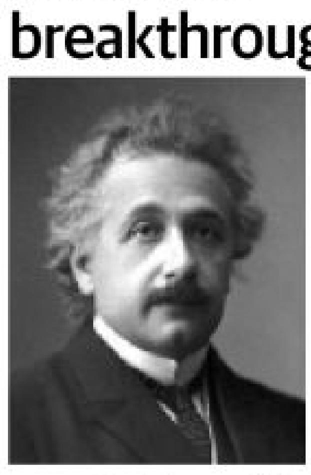
Hoyle and his team are using a familiar principle: "It's effectively an updated version of Cavendish's torsion balance, in a vacuum chamber with modern electronics. But to measure gravity at this scale you have to measure twists of the torsion pendulum of a nanoradian or better (a radian is a unit of angular measurement roughly equal 57 degrees). Imagine someone in London with a tennis ball that I'm trying to measure from California - that's the kind of angle we're trying to detect.

"At this point the motivation is really just to test how gravity behaves at that scale. There are various predictions from theories of dark energy that suggest gravity switches off entirely below a certain level and that also contributes to the accelerating expansion of the universe. The first thing, of course, would be to see a diversion, then the next challenge would be to explain it. If we can pick up on something, then we might be looking at evidence of extra dimensions, new forces or exotic particles. For me, it's a perfect project for undergraduates, because the physics of measuring gravity is something you can understand at that kind of level. Whether we make a groundbreaking discovery of new physics or not - well, who knows?"

Gravity shapes every aspect of our lives on Earth, holds our planet in orbit around the Sun and keeps our Solar System on its track around the Milky Way. It's responsible for some of the strangest and most extreme objects in the cosmos, for the large-scale structure of our entire universe and it even shapes the nature of time and space.

However, this dominant force, which challenges the fundamental theories of science precisely when we peek beyond our own sphere, can most of the time be accurately described by a scientific model over three centuries old. It seems that the more we learn about the workings of space, the more gravity's secrets come to light.

1911
Einstein's breakthrough

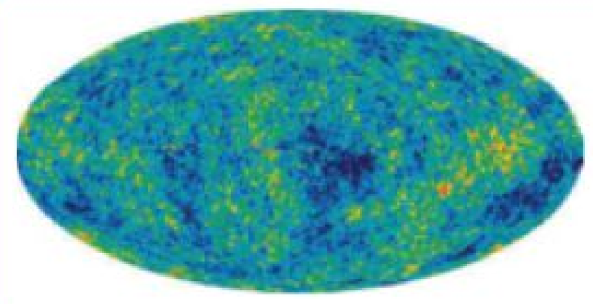

Einstein outlines the equivalence principle, realising that situations involving gravitational fields and those involving constant acceleration are actually physically identical.

1915
General relativity


Einstein publishes his theory of gravity, space and time. This is later proved by Arthur Eddington's 1919 observations of gravitational lensing, while viewing a solar eclipse from the island of Príncipe.

1967
Black holes

US physicist John Archibald Wheeler coins the term 'black hole' as part of his description of the way general relativity describes collapsing stars.

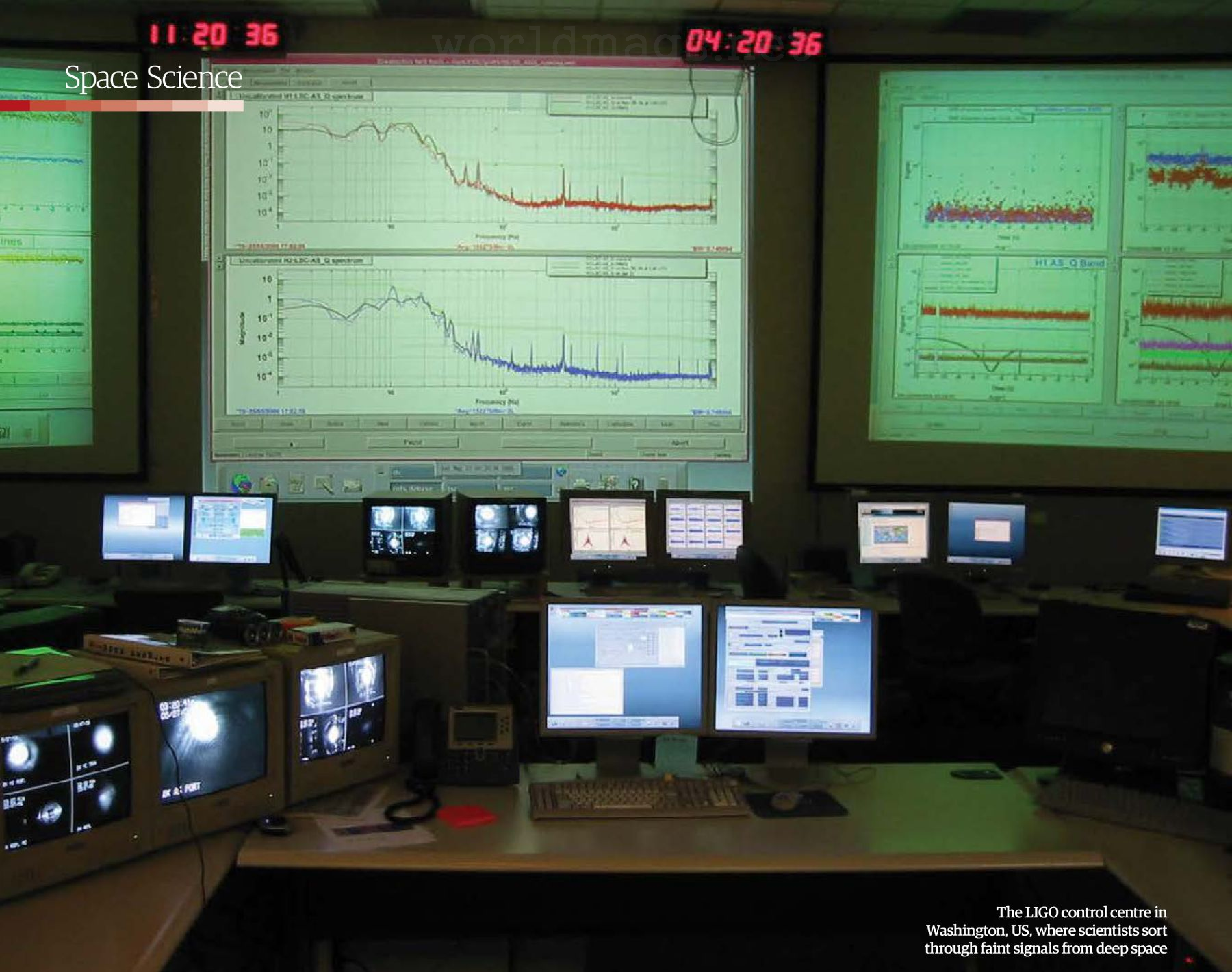


1998
Dark energy

Independent teams publish evidence that the expansion of the universe is accelerating, driven by an unknown force named dark energy, which could have key implications for gravity.

2014
Gravitational waves?

When Advanced LIGO comes online, it should open up a new area of gravitational astronomy by detecting gravity waves.



The LIGO control centre in Washington, US, where scientists sort through faint signals from deep space

Gravity's biggest mystery

Principal investigator for the GEO600 project, Professor Bernard Schutz, tells us about the hunt for the elusive gravitational wave with the LIGO collaboration's giant detectors

Could you explain exactly what gravitational waves are?
Gravitational waves are actually a very simple concept – they arise because nothing can travel faster than the speed of light, including the influence of changes in gravity. Gravity is always changing wherever we have masses – the sources of gravity – moving around, but those changes aren't felt instantaneously at a distance. Instead, they spread out at the speed of light through space – gravity waves are simply the effect of those changes finally reaching us.

Einstein's theory describes gravity in terms of the curvature of space-time and you can think of gravitational waves as little ripples spreading across curved space-time. The challenge is to find changes on a short enough timescale – most astronomical events happen slowly.

Can you tell us a bit about the origins of Laser Interferometer Gravitational Wave Observatory?
The project was approved in 1992 and always involved a two-stage plan with different levels of sensitivity. Between 2005 and 2010 they had two observing runs. As well as instruments in Louisiana and Washington State, the project works in conjunction with the VIRGO detector in Italy and GEO600, which is a German-British collaboration.

The scientific community worldwide worked on analysis, and after thorough examination they found no evidence of gravitational waves, but we didn't expect to detect waves at this first level of sensitivity. The point of this was to do the engineering and sort out the operational side of things.

Can you explain the principle behind these different detectors?
They all operate on the same basic principle of

interferometry; each detector sends laser light up and down two perpendicular arms. It goes up to the far end, bounces off a mirror, gets reflected back and you look at the interference patterns between the waves when they come back. The mirrors are suspended on a complex assembly that isolates them from external influences but still enables them to move. When a gravitational wave comes through, they should shift by very tiny amounts – perhaps 1/1,022 of the four-kilometre [2.5-mile] arm length. The mirrors in each arm typically move in different ways and as a result the paths of the two light beams get longer or shorter, so the interference pattern changes.

How does the second phase improve on the original?

The upgrade, called Advanced LIGO, is mainly about reducing noise – we've already evacuated the tubes and isolated the mirrors from the environment, but there are still random factors we can reduce such as friction between the mirrors and their supporting wires. The other major thing is an increase in laser power – the more light you have generating the interference pattern, the more accurately you can measure it. The original LIGO was capable of measuring 1/1,021 of its arm length and the new one is ten-times better.

What kind of objects do you hope to detect?

At both stages we're looking for neutron stars or black holes in binary systems that may spiral together and merge. These are rare events throughout the universe – the first stage of LIGO could have detected a neutron-star merger out to the distance of the Virgo Cluster (20 megaparsecs), but the final phase of the merger is what generates the intense gravitational waves, which happens in less than a minute.

We think these mergers happen in a galaxy like our own maybe once in 100,000 years. So you need something like 100,000 galaxies within range of your detector before you really have a chance of seeing these things regularly. The Virgo Cluster has about 1,000 galaxies, so it just wasn't rich enough, but when we extend our sensitivity by a factor of ten we could bring a million galaxies within range, so we'd expect to see tens or more of these events yearly.

"The challenge is to find changes [in the curvature of space-time] on a short enough timescale – most astronomical events happen slowly"

What is the Drake equation?

How many intelligent civilisations are there in the galaxy? Frank Drake's formula is both simpler and more complicated than it looks

In 1961 astronomer and astrophysicist Frank Drake, future founder of the SETI Institute (the Search for Extra Terrestrial Intelligence), constructed an equation designed to estimate the number of intelligent civilisations there are in the Milky Way. It brought together seven variables he thought were key to this formula, although it wasn't intended as an absolute solution. Rather, Drake had created what would come to be known as the Drake equation to prompt discussion at a meeting with space professionals, concerned with the search for extraterrestrial intelligence, .

As a means of calculating an exact value of intelligent extraterrestrial civilisations, it's deeply flawed. While powerful space telescopes and exoplanet observations in recent years have enabled astronomers to narrow down the first three variables, the latter four concerning the conception of life, evolution and intelligence are either difficult or impossible to tell.

With our current knowledge, a solution using this equation would put the number of intelligent extraterrestrial civilisations in the galaxy in the range of anything from zero to billions – not a very useful figure at all. However, as a way of promoting scientific thought and summarising what might constrain SETI's, if not the space industry's efforts to search for life, it's been very successful. The fact the Drake equation has endured 50 years and is still famous, is testament to that.

$R^* \times f_p \times n_e \times f_l \times$

Number of stars

The first parameter in the Drake equation estimates the average rate of star formation in the galaxy. Our galaxy produces around seven new stars every year, although in its youth it would have created 100 or more. The basic equation doesn't take into account the type of star: systems with short-lived, massive and hot stars are hostile to life.

Stars with planets

This calculates the fraction of those star systems that host planets. When the Drake equation was formulated the only known planets were in our own Solar System. Today, we know of nearly 2,000 exoplanets and it's thought that, on average, there's at least one planet for every star in our galaxy, putting this number in the hundreds of billions.

Habitable planets

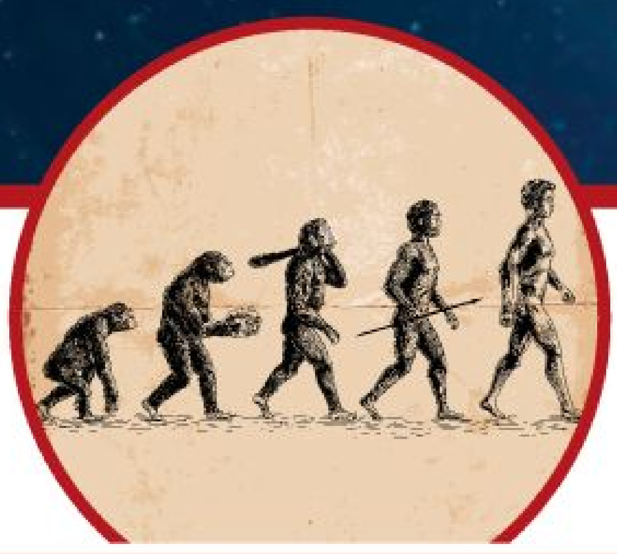
We've got a good idea of this part of the equation, which calculates the average number of planets capable of supporting life for every star that has planets. Drake gave this parameter an optimistic value of two, meaning two Earth-like worlds for every star with planets. Today we think one in five Sun-like stars has a planet that can support life.

Supports life

This is where the equation begins to fall apart. Because Earth is the only place in the universe where we know life has occurred, it's difficult for scientists to determine how easily life can form on other habitable planets. If we can find evidence of past life in our Solar System, we'll be more able to assign this parameter a more-accurate value.

The Fermi paradox

This famous argument was postulated by renowned physicist Enrico Fermi in the 1950s and bears some similarity to the Drake equation. Essentially, it states that if intelligent civilisations existed within our galaxy, then we would know about it already and Earth would have been visited, if not colonised by now. This means we are very much alone in this galaxy. The argument is that there are billions of older stars than the Sun, and unless Earth is an incredibly rare planet, some of them would have developed intelligent life. A few of these would have eventually formed interstellar civilisations, which could have colonised the entire galaxy in less than 100 million years. Fermi himself famously summarised this entire theory in a single pithy question: "Where is everybody?"



$$f_i \times f_c \times L = N$$

Intelligent life

If estimating the regularity of life occurring on habitable worlds in our galaxy is tough, then estimating the emergence of intelligent life is near-impossible. Life on Earth took around a billion years to emerge, but complex life was slower to evolve. Drake thought just 1 in 100 planets with life in the galaxy would go on to evolve sentient species.

Detectable life

There are a number of signs of extraterrestrial life that organisations like SETI look for, but they search for repeating patterns in radiowaves. The limitations of this form of communication are one reason why we haven't ever detected this kind of signal, but Drake thought that one in 100 civilisations would have the technology.

Detectable period

Extraterrestrial civilisations with interstellar communication may have existed or could exist in our galaxy, but we may either have missed their signals or won't be around to detect them in the future. Estimates for this parameter are upwards of 50 years, although Drake guessed a civilisation might remain detectable for 10,000 years.

Possible communication

Now we arrive at the solution: the number of civilisations in the Milky Way with which communication may be possible. The variability in each of the parameters that lead to this figure makes any hard solution from the equation an exercise in futility. It's a tangible way to communicate and educate people about the search for life, however.

Is life from MARS?

Could we all be Martians? We put the theory that life on Earth is of extraterrestrial origin under the microscope

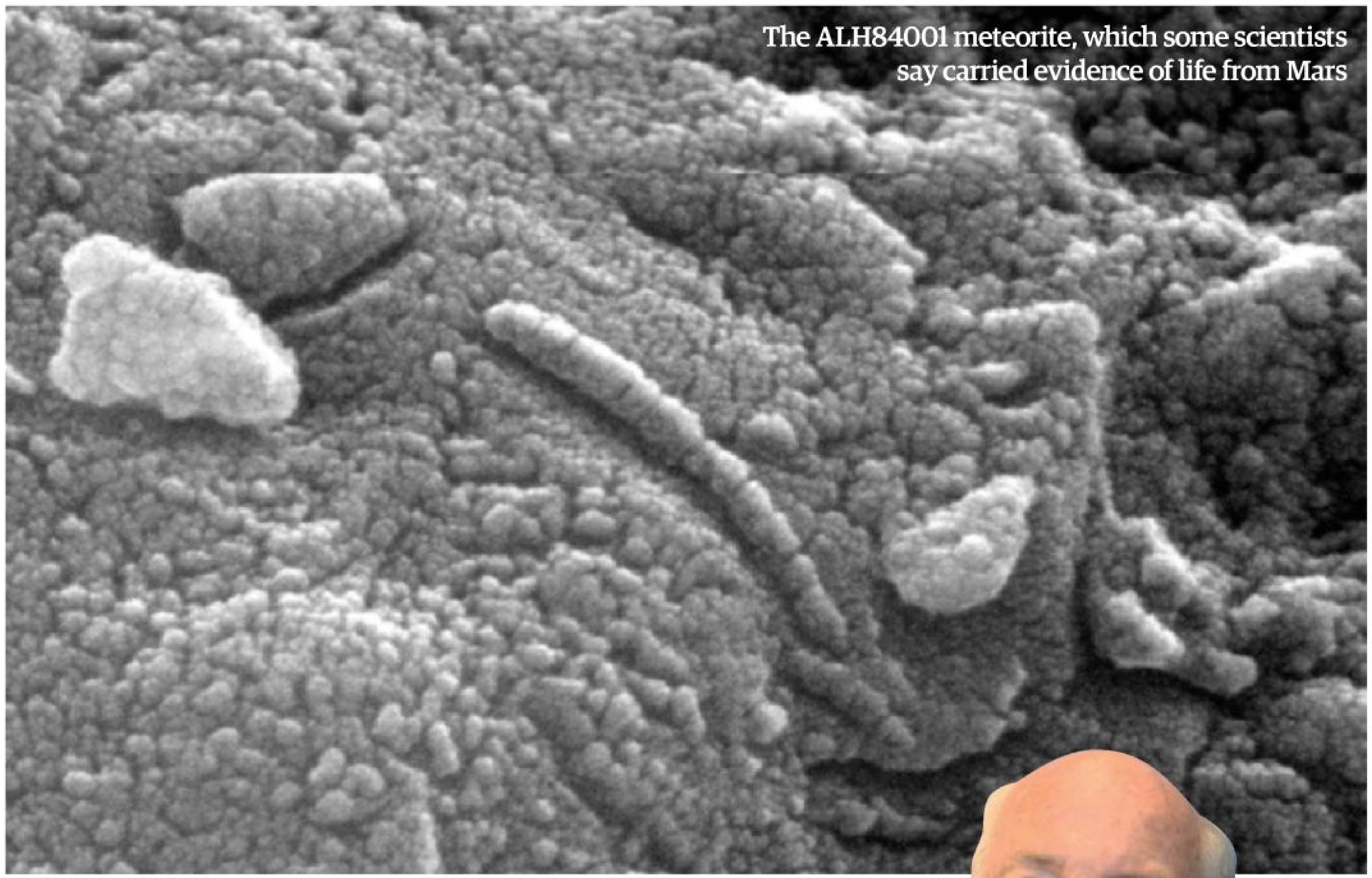
Around 4 billion years ago the chemical constituents of life stewed in a primordial soup on Earth. Gradually, over time, this formed primitive single-celled microbial life, which later evolved into multi-cellular life. Over the next few billion years this life gradually evolved into the species that inhabit the Earth today, from plankton to people. Those first ingredients of life formed on Earth itself, with no external input.

That's the widely accepted theory as to how life on Earth began, but not all are convinced. Some are sure that life on Earth began elsewhere, being transferred to Earth by comets or asteroids, where it gained a foothold and evolved into modern life forms. One theory that has risen to the fore in the last few years is that this life originated on Mars, given credence by the discovery made by NASA's Curiosity rover that the Red Planet was almost certainly wet, and possibly habitable, in its distant past.

It's a theory that has been met with harsh criticism at worst, and mild trepidation at best. 'Extraordinary claims require extraordinary evidence,' is an oft-quoted retort to such theories, but some scientists are convinced that such extraordinary evidence is not beyond our reach.

One of the main proponents for life originating on Mars is Professor Steven Benner of the Westheimer Institute of Science and Technology in Gainesville, Florida, USA. Presented at the Goldschmidt Meeting in Florence, Italy earlier this year, Benner described how the early conditions on Mars might have been more suited to the building blocks of life than the young Earth.

Life as we know it requires three crucial ingredients, namely RNA, DNA and proteins. RNA, or ribonucleic acid, forms through a difficult process of 'templating' atoms on the crystalline surface of minerals. The minerals required for this templating to occur would likely have dissolved in the seas of the young Earth if it was covered in a global ocean, as has been suggested, but they could have more easily existed on a drier Mars according to Benner.

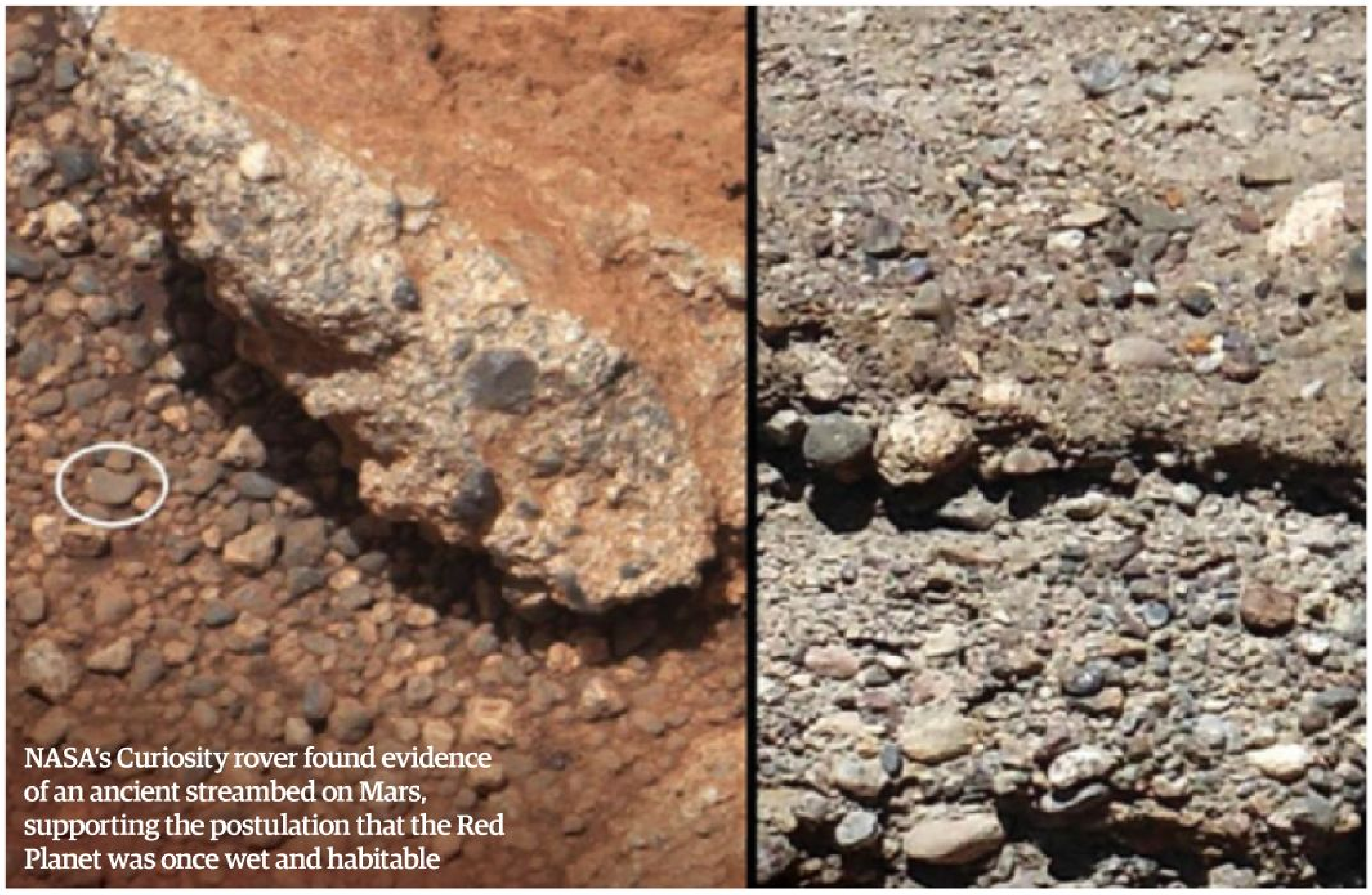


The ALH84001 meteorite, which some scientists say carried evidence of life from Mars

"I would certainly give my odds of life originating on Mars as right now about 50:50"

Dr David Deamer

"I would certainly give my odds of life originating on Mars as right now about 50:50," explains biochemist Dr David Deamer of the University of California, Santa Cruz, USA. "I think Mars, at one point, based on recent observations, had the kind of conditions that would allow simple replicating systems to appear. The question of whether these then were delivered to Earth is much more problematic, and it's a possibility although I don't think necessarily a plausibility."



NASA's Curiosity rover found evidence of an ancient streambed on Mars, supporting the postulation that the Red Planet was once wet and habitable

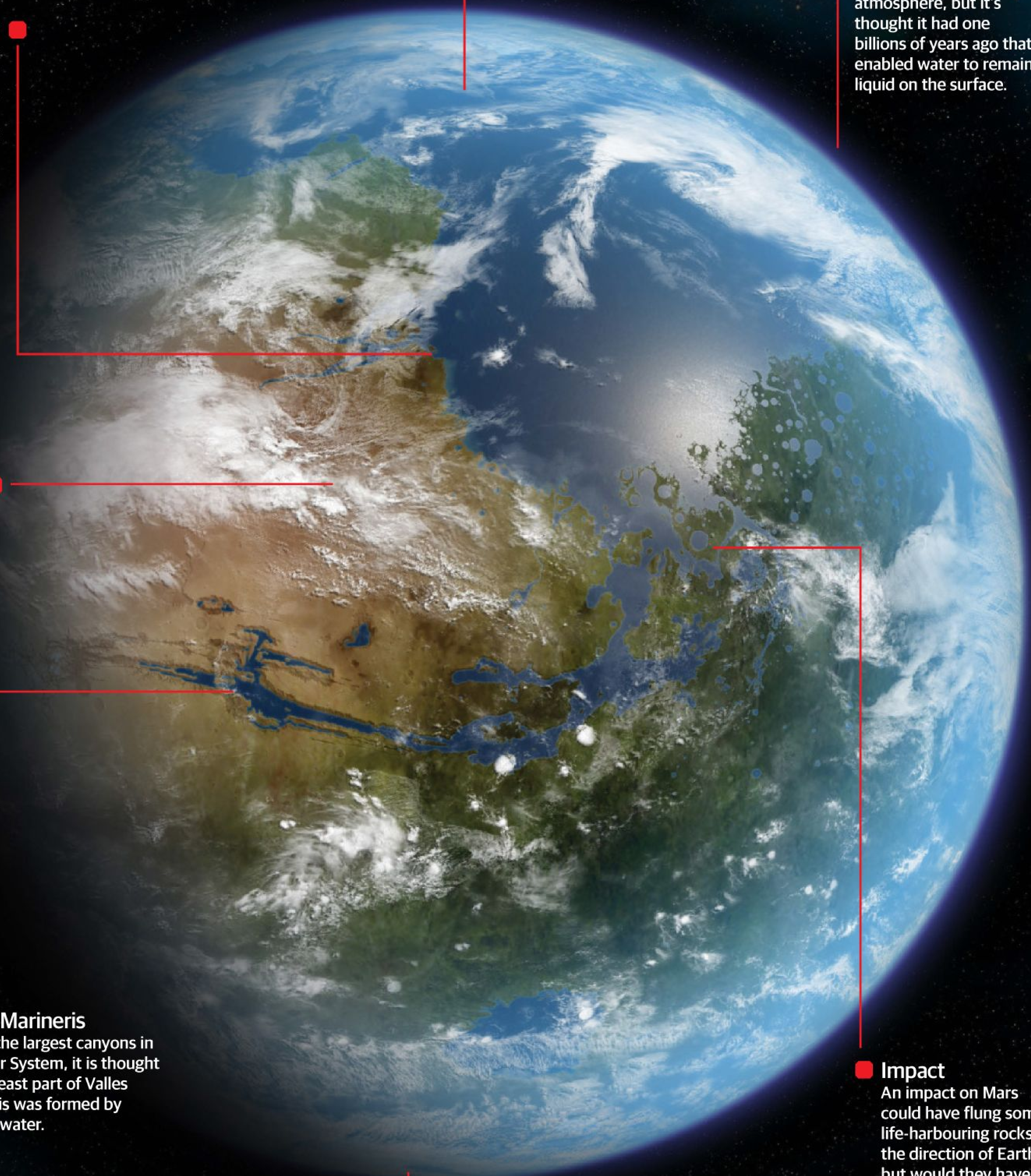
Benner's research is based around the assumption that Earth was once wholly covered in water. This might sound conducive for life but, in fact, it is quite the opposite. Life is dependent upon polymerisation chemistry, which is the process through which simple monomer molecules are reacted together to form complex polymers. In basic terms, life forms through the bonding of simple molecules, such as amino acids and nucleotides, into polymers such as proteins and nucleic acids respectively.

For this to happen, however, water molecules need to be pulled from between monomers. If Earth really was once covered in a global ocean, as Benner suggests, then this would have been incredibly unlikely to occur. For monomers to form polymers, there needs to be a wetting and drying environment, something a completely wet Earth could not provide.

Benner says that while Earth was covered in a global ocean, Mars was not. The Red Planet instead only had shallow oceans where the minerals essential for the origin of life would have been more likely to occur. Dr Deamer, however, isn't so convinced by this aspect of the theory.

Our observations of Mars heavily suggest that it would have had volcanic activity that would have caused land to rise up from the oceans, producing large land masses on the Red Planet where life could form. Benner's assumption is that this same volcanic activity did not occur on Earth 4 billion years ago. "My disagreement arises from his assumption that Earth was covered by a global ocean," says Dr

Is this what Mars once looked like?



Northern hemisphere
The northern hemisphere of Mars is at a much lower elevation than the southern hemisphere, leading some scientists to speculate it was once the location for a huge ocean.

Atmosphere
Mars has since lost its atmosphere, but it's thought it had one billions of years ago that enabled water to remain liquid on the surface.

Wet and dry
Life would have more easily formed at the boundary of water and land where it could have gone through the wetting and drying process needed to evolve.

Volcanic activity
Research suggests that many of the land masses at higher elevation we can see on Mars today were formed by volcanic activity in its past.

Valles Marineris
One of the largest canyons in the Solar System, it is thought that at least part of Valles Marineris was formed by flowing water.

Impact
An impact on Mars could have flung some life-harbouring rocks in the direction of Earth, but would they have survived the journey?

Poles
Evidence for water on Mars remains at the poles, where large quantities of ice are still present in the modern day.

5 reasons life might have come from Mars...

1 Earth was too wet

If Earth was indeed once covered in a global ocean, it would not have been able to support the constituents of life as they would probably also require dry land.

2 Mars was once habitable

Evidence suggests that Mars not only had water in its past but also a thicker atmosphere, which would have enabled life to form on its surface.

3 Rare bacteria

Some rare forms of bacteria have magnetite that can be used as a biological compass to follow the magnetic field of Earth. They have also been found in the Martian Allan Hills meteorite.

4 Meteorites reach Earth

We know that meteorites (some from Mars) regularly make it to Earth, even in the modern day and much more so in the past. Could one of these have brought the ingredients for life?

5 Volcanic activity

Mars is thought to have been volcanic in the past, which would have provided land upon which primitive life could form.

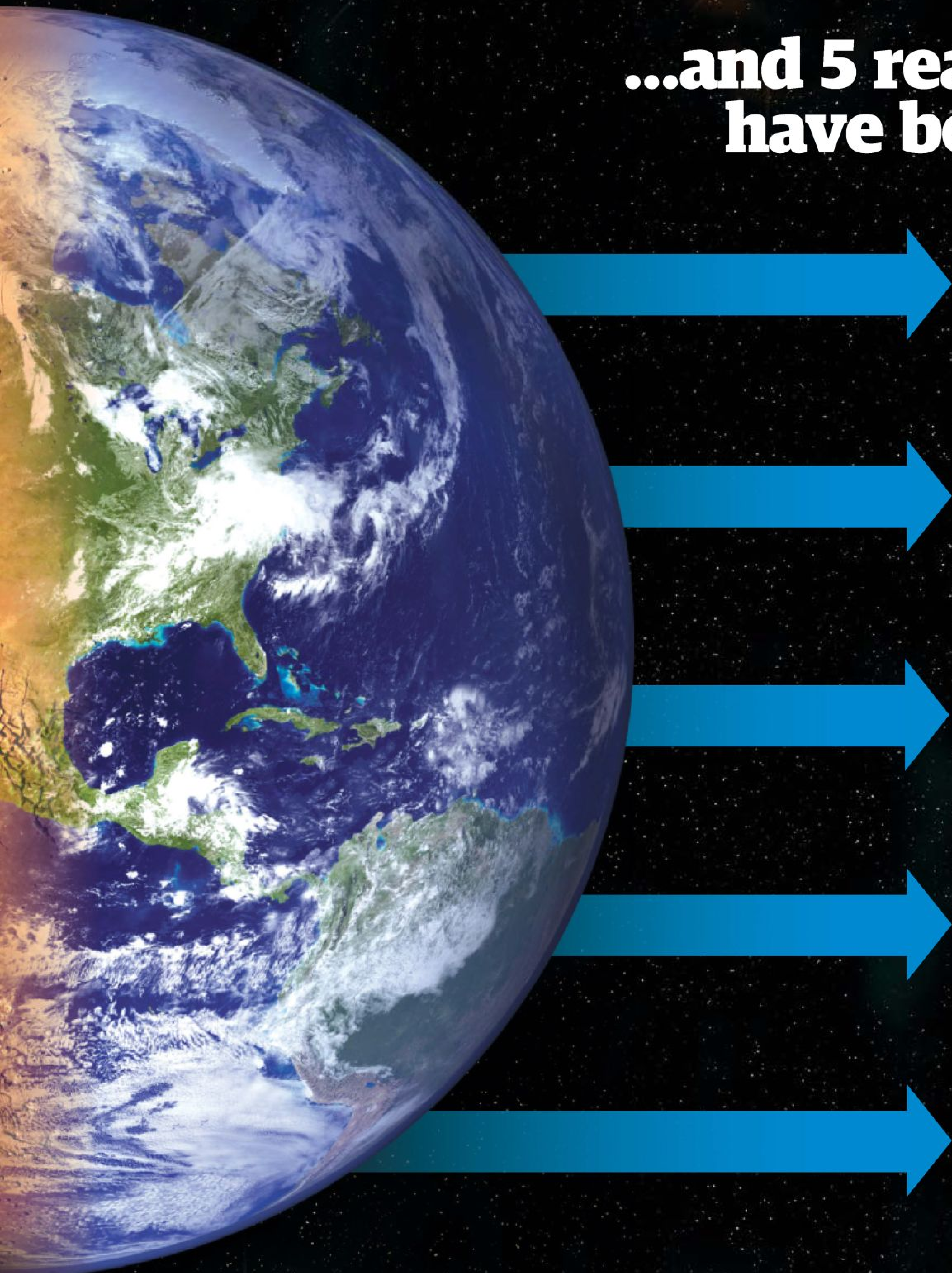
Deamer. "Mars had volcanic activity without a doubt, but I don't see any reason why those same volcanic activities would not have occurred on Earth and that volcanoes would have arisen out of the early ocean."

Evidence for this occurring on Earth is apparent due to islands such as Hawaii and Iceland, so Dr Deamer suggests "it's likely that we had volcanic activity producing land masses above the global ocean, and this was likely the case on Mars as well."

If this was the case, there's no reason that life could not have begun on Earth. In fact, Dr Deamer and his team are currently in the process of finalising some groundbreaking research into producing life akin to what might have been on Earth 4 billion years ago. "We're now at the point where we can put together in the laboratory systems of molecules that have some of the properties of a primitive form of life," explains Dr Deamer. "We haven't got that to reproduce yet, but I can see looking just a few years in the future that the progress is such that we will have a laboratory

> "Many meteorites from Mars have landed on Earth and it is on these meteorites that Benner suggests life could have been transported"

...and 5 reasons it might have begun on Earth



1 Life could have formed here

Most evidence suggests that Earth had a volcanic beginning just like Mars, which means it would have had land masses upon which life could form.

2 It was habitable

Unlike Mars we know for certain that Earth was and still is habitable as we're still here and there's evidence for life stretching back to the earliest of days.

3 The distances are extreme

Life travelling from Mars on an asteroid to Earth would have to make a daunting journey of 225 million kilometres (140 million miles), which leads us to...

4 Harmful radiation

The journey from Mars to Earth is fraught with peril, not least from the huge amounts of radiation that would kill any unprotected life attempting to migrate.

5 We're yet to find extraterrestrial life

Theories of life existing elsewhere, let alone originating there, are pure conjecture. So far there is only one world in the universe we know to have life, and that is Earth.

demonstration of a replicating chemical system that has the properties of life."

Benner's theory continues that, assuming life did begin on Mars and not Earth, there is then the issue of how this life was transported to our planet. Many meteorites from Mars have landed on Earth, having undertaken journeys of millions or perhaps billions of years, and it is on these meteorites that Benner suggests life could have been transported.

One such meteorite, known as Allan Hills (ALH) 84001, is a popular piece of evidence favoured by proponents of the 'life from Mars' theory. The meteorite, which was discovered in Allan Hills, Antarctica in late December 1984, was thought by some to contain microscopic fossils of Martian bacteria. The presence of this fossilised bacteria, however, is the cause of much contention. If true, it would confirm that life really could have begun on Mars and, perhaps, the ingredients for life on Earth could have been transported by an asteroid. The theory is that ALH 84001 was blasted from the surface of Mars around 4 billion years ago before making its journey of 225 million kilometres (140 million miles) to Earth.

"The main deal [with ALH 84001] was that things looked like they might be fossils," says Dr Deamer, "and that was done using a scanning electron microscope and, sure enough, there's stuff that looks like it might be fossilised bacteria. However, there are a bunch of minerals that can also look similar to that, and if you're going to make an extraordinary claim like 'this is a fossil', you must have extraordinary supporting evidence. When people looked at all that evidence critically they were not convinced. It was not sufficient to get the jury of peers who are critical and sceptical scientists to agree."

In January 2013, scientists on NASA's Astrobiology Icy Worlds team ran experiments to see if organic molecules could be brewed in a simulated ocean like that found on the young Earth

Another problem with the suggestion that life was carried to Earth on an asteroid is the enormous distances mentioned earlier. Space is a harsh environment; outside the protective magnetosphere of Earth, radiation from the Sun and outside the Solar System is deadly to almost all forms of life. Some meteorites are thought to have taken hundreds of millions or billions of years to reach Earth, and for any form of life to survive that long on an asteroid seems somewhat implausible. Some suggestions that life could reside inside such space rocks is also unlikely, as the relatively small size of asteroids would be unlikely to provide sufficient protection from harmful radiation.

This is where another theory of life on Earth being of extraterrestrial origin, true panspermia, has been met with unreserved scepticism. True panspermia is the theory that life did not originate on Earth, but nor did it originate on Mars; proponents of this theory suggest that life began elsewhere in our galaxy, perhaps in another planetary system, before being transferred here.

One proponent of this theory is the somewhat controversial astronomer Chandra Wickramasinghe, professor and director of the Buckingham Centre for Astrobiology at the University of Buckingham, UK, whose theories of true panspermia, which he formed alongside the late astronomer Sir Fred Hoyle, have been met with a critical reception.

"The total [number of exoplanets] has been reckoned by some NASA scientists at 144 billion Earth-like planets in our Milky Way alone," explains Wickramasinghe. "If you accept that estimate then the nearest Earth-like planet to us is only three or four light years away, which is sort of spitting distance in cosmic terms. So the position I have maintained is that life on Earth is most unlikely to have originated on Earth."

Wickramasinghe's view of true panspermia is that all life began at a similar time at the dawn of the universe, spreading between the planets and stars in the process. It's a contentious theory to say the least; there's not a lot of evidence to support it. "The whole process of the origin of life occurred maybe very early in the history of the universe, maybe in the first 100 million years after the Big Bang," he says. "This was when the universe was compact, much smaller than it is now, and communication between one planetary system and another was more intimate. I think life began not in a puddle on Earth, but in the totality of a planetary puddle that existed at the dawn of the universe. There's no way that life can be confined to one place, is my conclusion."

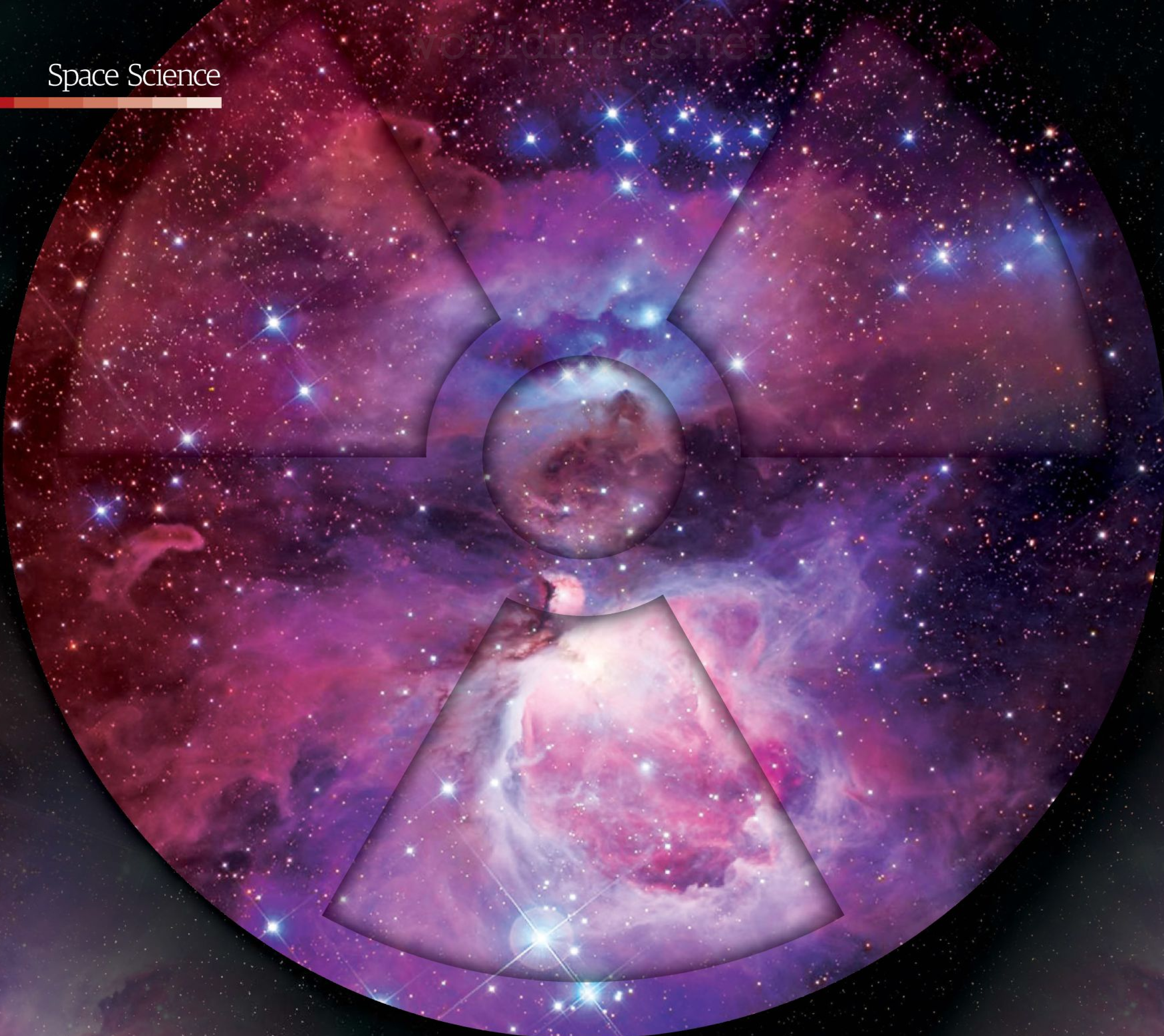
Dr Deamer, however, was quick to point out a key problem with true panspermia. "If you look at the distances involved in true panspermia, things getting to us from other solar systems in our galaxy, the mathematics make it virtually inconceivable that anything could travel those distances and stand up to cosmic radiation long enough to make it to Earth," he explains. "So you've really got to look at the maths and the physics of what would be required to get something even from the nearest star about four light years away travelling at way below light velocity to get here. These things would take billions of years to get here and they'd be exposed to all kinds of ionising radiation in the interim, so it just seems highly implausible that panspermia is going to stand up to that kind of critical analysis."

While true panspermia might seem a bit far-fetched for now, the possibility of life originating on Mars is one that certainly merits further investigation. As is the case with theories of this sort, however, Occam's razor often holds true: the simplest answer, in this case that life began on Earth, is normally correct.

"We do know that pieces of Mars get to Earth, we do know that organic compounds were probably on Mars and we do know that [those compounds] could come in a Martian meteorite," surmises Dr Deamer. "In scientific judgement it's still at a level of being implausible, but it's less implausible than true panspermia."

So, are we Martians? It'll take some extraordinary evidence to prove that we are originally from the Red Planet but maybe, just maybe, that evidence is just waiting to be found.

"While true panspermia might seem a bit far-fetched, the possibility of life originating on Mars is one that certainly merits further investigation"



DEADLY SPACE RADIATION

How cosmic rays and solar wind could hamper our efforts to explore deep space


The ground-based VERITAS array in Arizona, USA is used to measure low-energy cosmic rays

Radiation has been a known problem for space exploration since the dawn of the space age. Early ventures into the cosmos were met with trepidation as it was unknown what effects radiation would have on astronauts as they moved out of the protective atmosphere of Earth. Thankfully those early explorers returned safely from their brief forays into the unknown, but long-term exposure to radiation is still a potentially fatal danger that must be addressed if mankind is to journey into deep space.

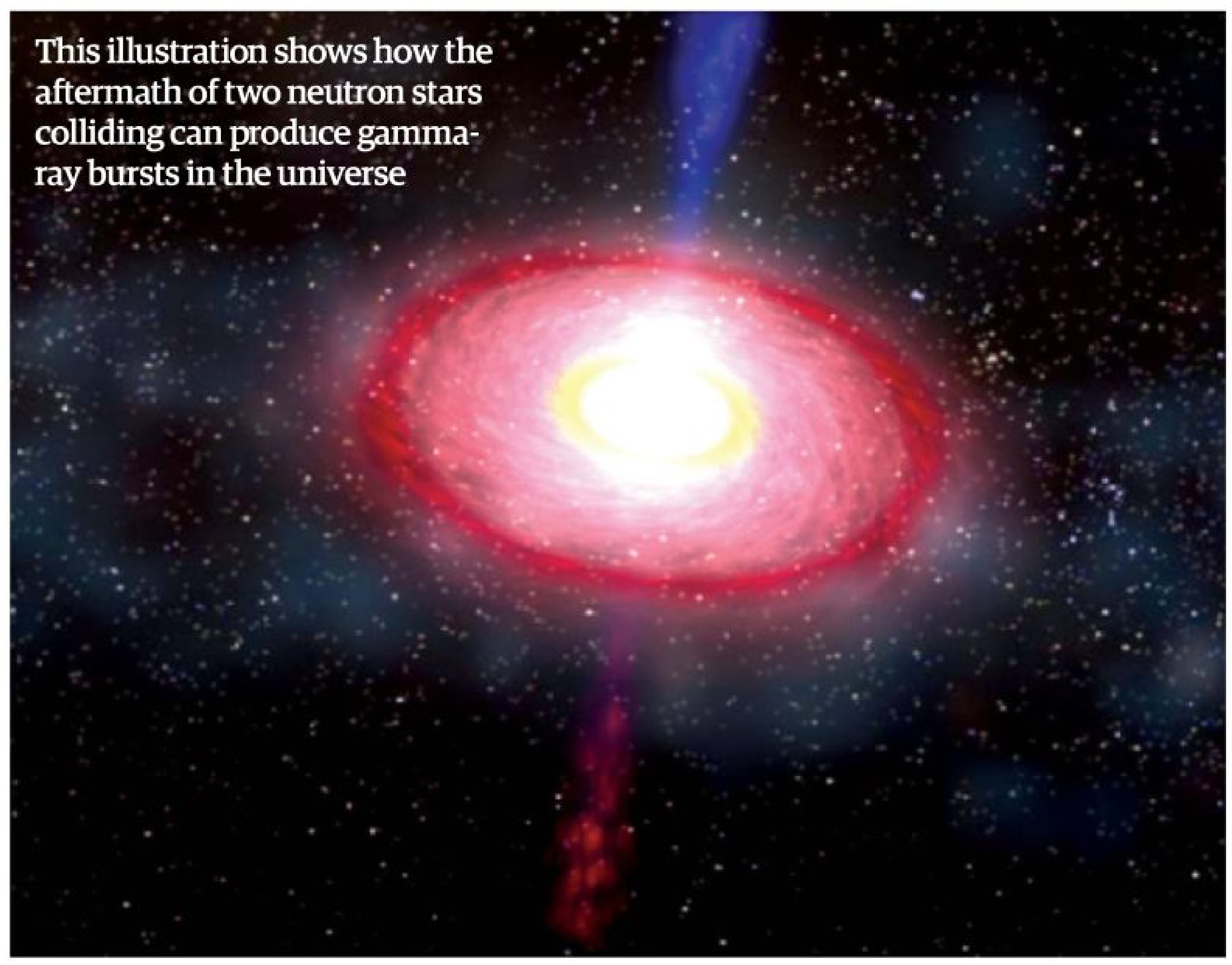
Radiation in the Solar System originates from a number of sources, with the primary source of radiation near Earth being the Sun. Sunlight itself is a form of radiation - mostly ultraviolet, visible and infrared - that is largely harmless unless humans are exposed to it for a prolonged period of time. Long exposures can result in an increase in skin cancer, among other harmful effects. Thankfully, Earth's atmosphere does a pretty good job of protecting us from the damaging effects of solar radiation.

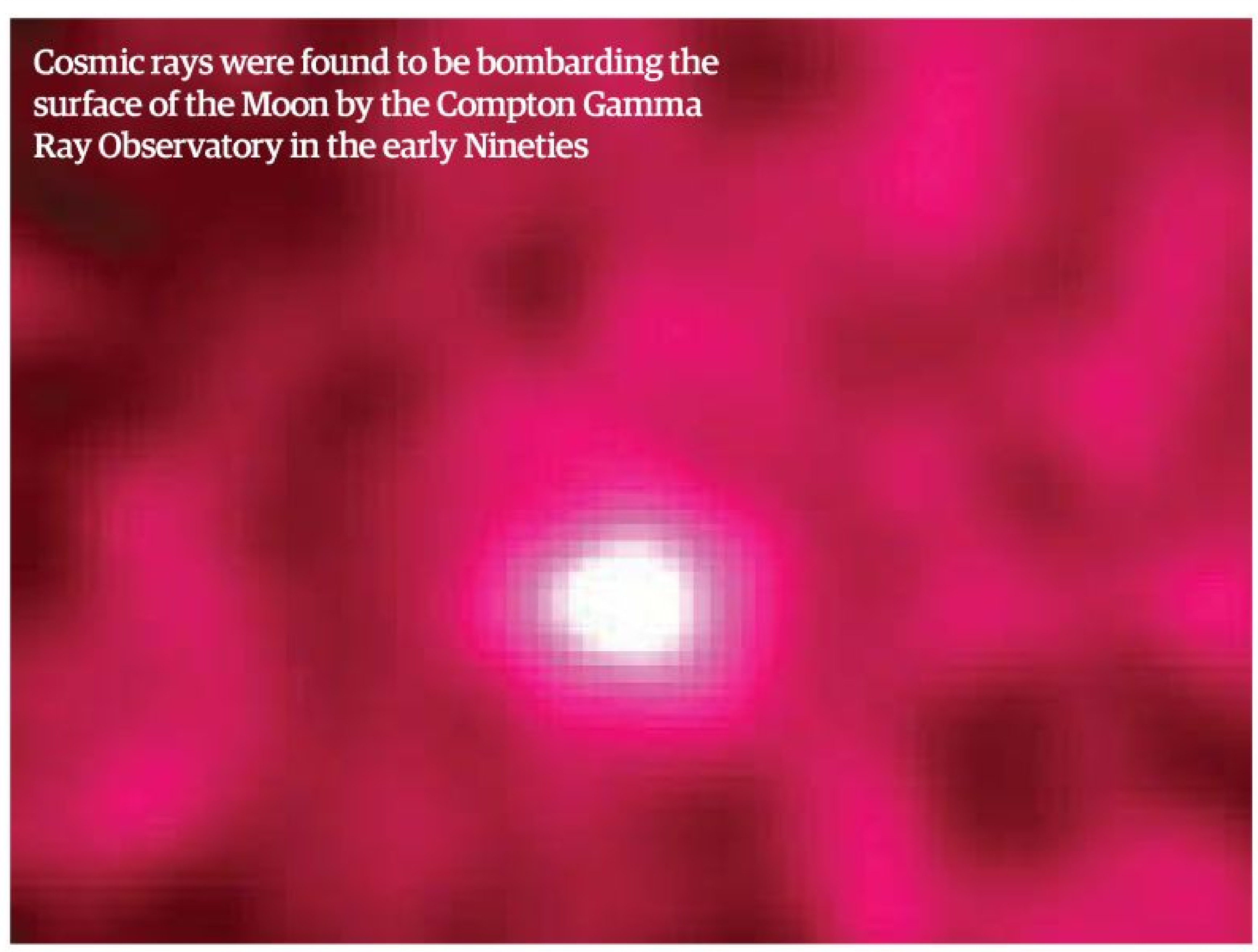
Our planet is also protected by its magnetosphere, which consists of magnetic fields surrounding the Earth that deflect incoming radiation. Within these magnetic fields charged particles are trapped in two regions known as the Van Allen radiation belts. The belts themselves are dangerous for astronauts to traverse, but Earth's magnetosphere prevents this radiation harming humans on the surface.

When astronauts venture out of the confines of low Earth orbit, away from the combined protective area of Earth's magnetosphere and atmosphere, they are subjected to higher levels of radiation that can be damaging. And it's not just the Van Allen belts that pose a threat; Apollo astronauts to the Moon had to ensure they did not spend a large amount of time on the lunar surface as incoming solar radiation could have been fatal.

Proton events, or proton storms, are extreme outbursts of energy from the Sun that occur whenever it emits a solar flare or a CME - a coronal mass ejection. When solar protons are charged to extreme energy levels by these events, large bursts of them are capable of penetrating the magnetic field to ionise the upper atmosphere of the Earth and create auroral-like phenomena. We're safe from them at low altitudes but spacecraft and astronauts are vulnerable, damaging sensitive instruments and afflicting exposed spacewalkers with lethal doses of radiation. Fortunately, we can shield astronauts and, to a certain extent, predict dangerous solar events, but they still pose a major obstacle to a potential manned mission to Mars.

Solar wind and energetic solar events, however, are not the only form of radiation that is a threat to astronauts. More troublesome are cosmic rays originating outside the Solar System, which we still know very little about. Huge cosmic events are known to emit large amounts of radiation that propagate through the vacuum of space, often bombarding our own Solar System. One such event is a gamma-ray burst (GRB), a huge outpouring of energy that can release more electromagnetic radiation in ten seconds than the Sun will emit in its entire 10 billion year lifetime. As Ben


This illustration shows how the aftermath of two neutron stars colliding can produce gamma-ray bursts in the universe


Cosmic rays were found to be bombarding the surface of the Moon by the Compton Gamma Ray Observatory in the early Nineties

"Gamma rays are energetic enough to rip DNA apart"

Ben Gompertz

Gompertz, a postgraduate researcher studying GRBs, explains, GRBs are an example of just how hostile the universe can be.

"Gamma rays are extremely harmful things," says Gompertz. "They're energetic enough to rip DNA apart. Prolonged exposure to an unrealistic level of GRBs could be a threat, but I don't think the amount contained in a single burst would do noticeable damage to a human. The gamma rays from the Sun would kill you before those from a GRB even got started."

Indeed, in our own Milky Way we are yet to observe a GRB. That may be because "the satellites we use to detect them, Swift and Fermi, don't typically point into the galactic plane due to the noise," says Gompertz. "That means we could well be missing them, although the rate across the universe of something like one or two a week suggests that the rate locally will be negligible if you account for the volumes in consideration."

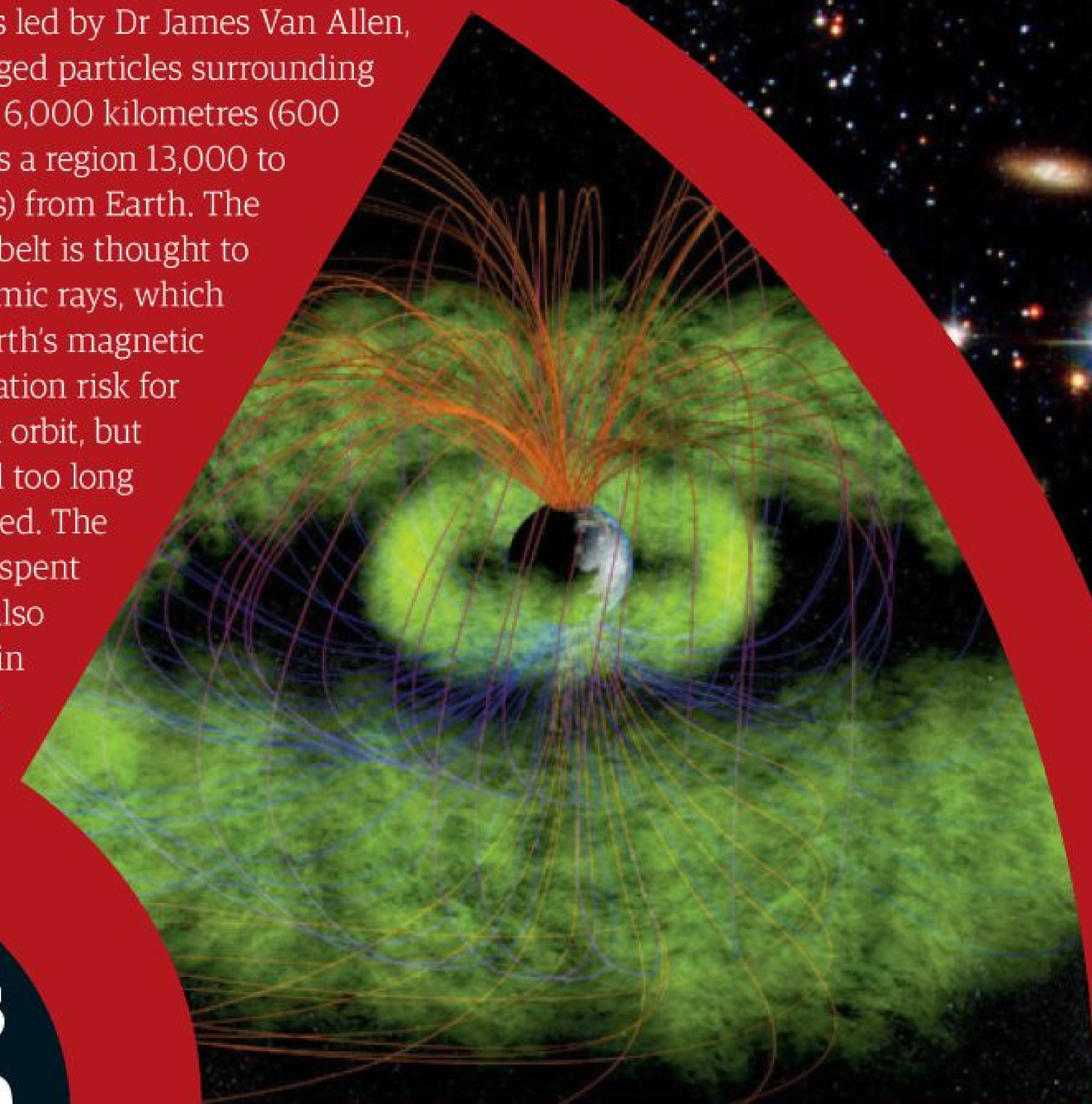
Regardless, however, GRBs are an unnerving reminder of how dangerous the universe can be. GRBs might be somewhat of a rarity, but the threat of other cosmic events producing gamma radiation, and other types of radiation, is a much more apparent threat. For example, at the heart of the Milky Way a supermassive black hole is thought to be churning out huge amounts of cosmic rays. Supernovas, meanwhile, can also throw off a large number of high-energy photons in our direction.

Some forms of radiation can be thwarted by a few inches of lead plating on spacecraft, but protecting against all types of cosmic rays isn't easy. With a small amount of shielding

Sources of space radiation

Van Allen belts

Discovered in 1958 by a group of American scientists led by Dr James Van Allen, the Van Allen radiation belts are two areas of charged particles surrounding the Earth. The inner belt extends from 1,000 to 6,000 kilometres (600 to 3,700 miles), while the outer belt occupies a region 13,000 to 60,000 kilometres (8,000 to 38,000 miles) from Earth. The origin of the high-energy particles in the belt is thought to be a combination of solar wind and cosmic rays, which are trapped within the belts by the Earth's magnetic field. The Van Allen belts pose a radiation risk for astronauts travelling beyond Earth orbit, but as long as astronauts do not dwell too long in them the effects are minimised. The Apollo missions, for example, spent little time in the belts and also used layers of aluminium in the command module to provide protection.



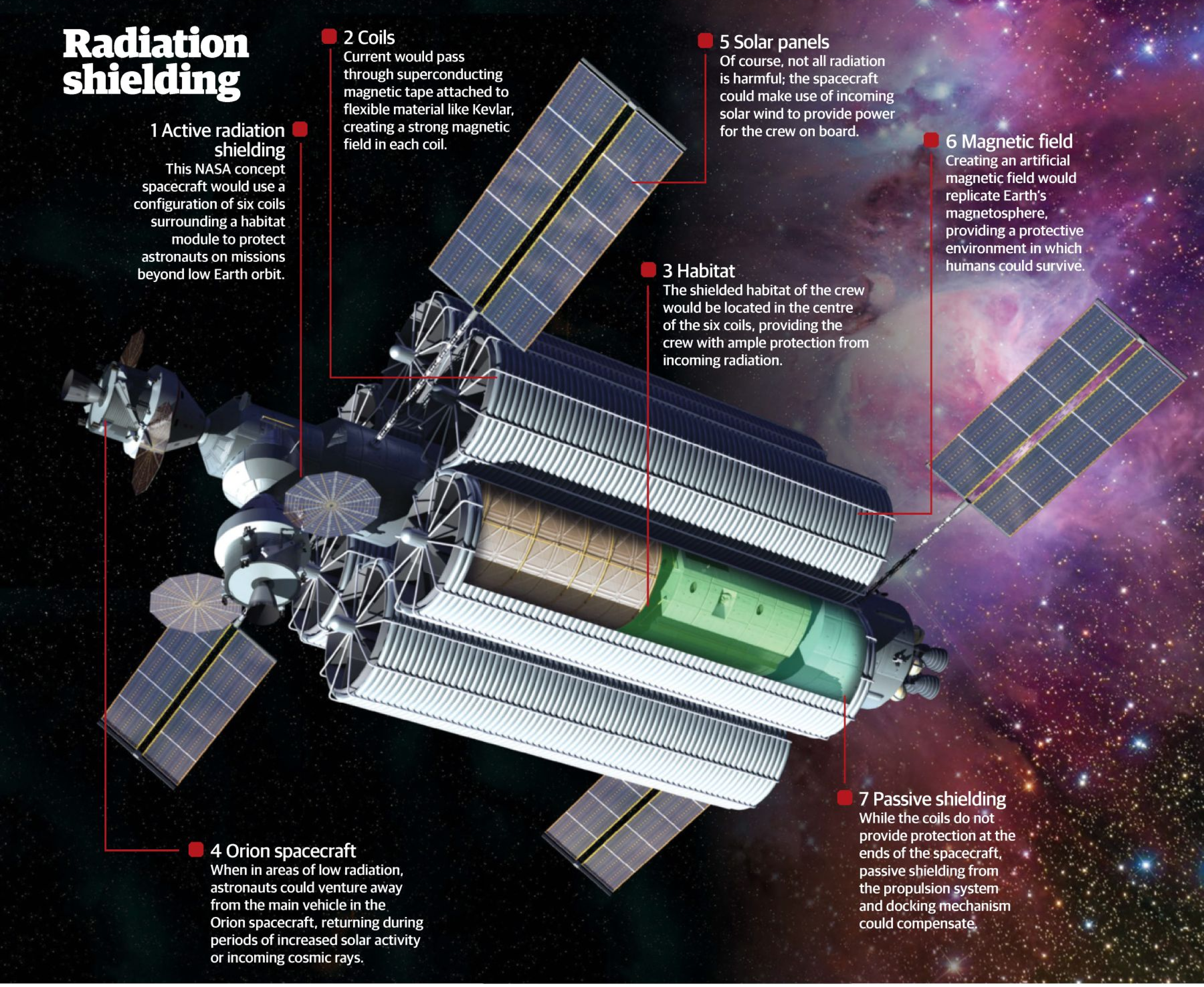
Cosmic rays

The most dangerous form of radiation traversing the galaxy is that coming from cosmic sources outside our Solar System. Supernovas, black holes and other massive events in the universe are known to emit supercharged subatomic particles that cannot be sufficiently stopped with any modern shielding technology. Fortunately, astronauts in low Earth orbit are relatively safe as the Earth's magnetosphere provides suitable protection. For astronauts venturing into the outer reaches of the Solar System, however, cosmic rays will be a significant threat. Over time, cosmic radiation can, among other effects, break DNA, induce radiation sickness and cause cancer. Ultimately, prolonged exposure to powerful cosmic rays could be fatal. It is this type of radiation that future astronauts will have to be most wary of.

Solar wind

While solar wind can be potentially fatal to exposed astronauts, it actually also has a rather beneficial effect that provides them with a natural source of protection. The Sun is constantly emitting high-energy protons, which, during periods of low solar activity, cause few problems to space-based humans. However, during periods of increased activity, particularly a coronal mass ejection (CME) accompanied by a solar flare, a large swath of radiation can be sent out into the Solar System. The hulls of most modern spacecraft, however, are sufficient to block most of this radiation. Only astronauts taking part in EVAs, or spacewalks, need to be especially wary. Solar wind also carries with it magnetic fields that deflect harmful charged particles originating elsewhere in the Milky Way. This is known as the 'Forbush decrease', and it is a useful source of protection from cosmic radiation.

Radiation shielding



> "The gamma rays from the Sun would kill you before those from a GRB even got started" **Ben Gompertz**

some incoming rays will make the shielding become radioactive, giving off secondary forms of radiation that can be harmful to a human crew. When it comes to cosmic rays, only an innovative method of shielding such as layers of water or superconducting magnets would be sufficient to protect astronauts from the adverse effects of being exposed to this radiation during a deep space exploration mission.

The effects of prolonged exposure to space radiation can be dangerous, to say the least. An unprotected astronaut exposed to solar radiation and cosmic rays for two hours would have their DNA ripped apart, or ionised. Even astronauts inside a spacecraft with some form of metallic shielding would ultimately develop an increased risk of cancer and probably succumb to some form of radiation sickness. The full list of effects from space radiation is lengthy, and also includes a higher risk of radiation cataracts - partial blindness - among astronauts.

Ultimately, to protect astronauts from the adverse effects of solar radiation we will need to devise new forms of shielding. There are several technologies being developed that may be able to reduce the hazard posed to human spaceflight by cosmic rays. Spacecraft, for example, could make use of material shielding such as liquid hydrogen or water to form a protective layer around certain areas of a spacecraft, which the crew could move to during increased elevated levels of incoming radiation. Magnetic deflection, as illustrated below, could also be used to deflect charged particles and keep the crew safe.

Tackling deadly space radiation will be a cause for concern when we decide to send astronauts to an asteroid, Mars or beyond. Some breakthroughs in key areas of technology are needed to ensure the safety of said astronauts, but hopefully with the multitude of research being done today a solution will soon be found.

Danger zones

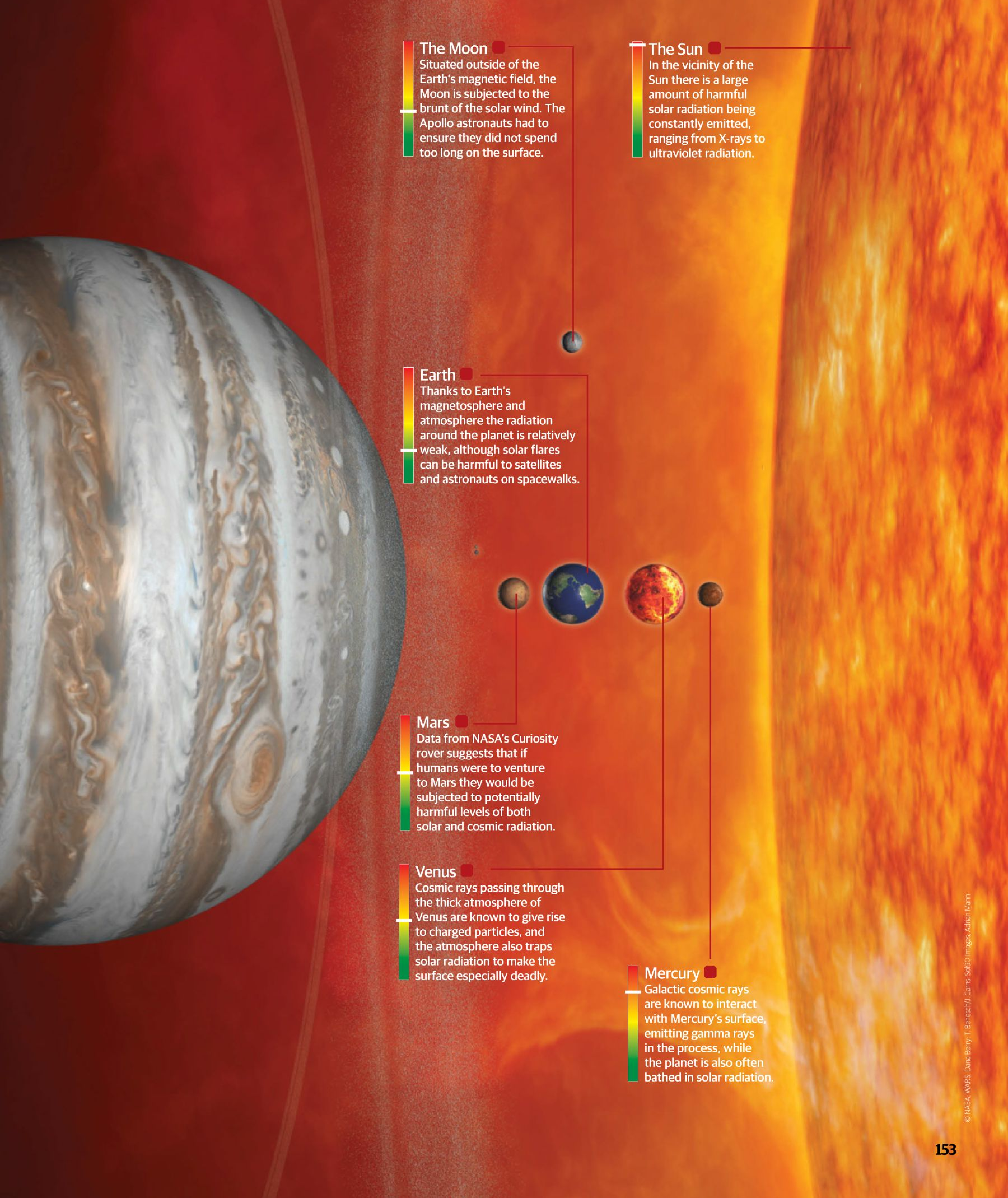
How do levels of radiation differ around the Solar System?

Jupiter

Like Earth's Van Allen belts, Jupiter accumulates particles in radiation belts that would pose a threat to any humans in the Jovian system. The Galileo spacecraft was severely damaged by Jupiter's radiation in the early 2000s.

Outer Solar System

As you venture out of the Solar System the strength and abundance of cosmic rays becomes more and more apparent, to the point that they can cause serious damage to humans or spacecraft.



The Moon
Situated outside of the Earth's magnetic field, the Moon is subjected to the brunt of the solar wind. The Apollo astronauts had to ensure they did not spend too long on the surface.

The Sun
In the vicinity of the Sun there is a large amount of harmful solar radiation being constantly emitted, ranging from X-rays to ultraviolet radiation.

Earth
Thanks to Earth's magnetosphere and atmosphere the radiation around the planet is relatively weak, although solar flares can be harmful to satellites and astronauts on spacewalks.

Mars
Data from NASA's Curiosity rover suggests that if humans were to venture to Mars they would be subjected to potentially harmful levels of both solar and cosmic radiation.

Venus
Cosmic rays passing through the thick atmosphere of Venus are known to give rise to charged particles, and the atmosphere also traps solar radiation to make the surface especially deadly.

Mercury
Galactic cosmic rays are known to interact with Mercury's surface, emitting gamma rays in the process, while the planet is also often bathed in solar radiation.

Future Tech

See how we're planning to explore and expand into space

"The GMT will provide ten times as much detail as the Hubble Space Telescope"

170
Billion-dollar telescopes

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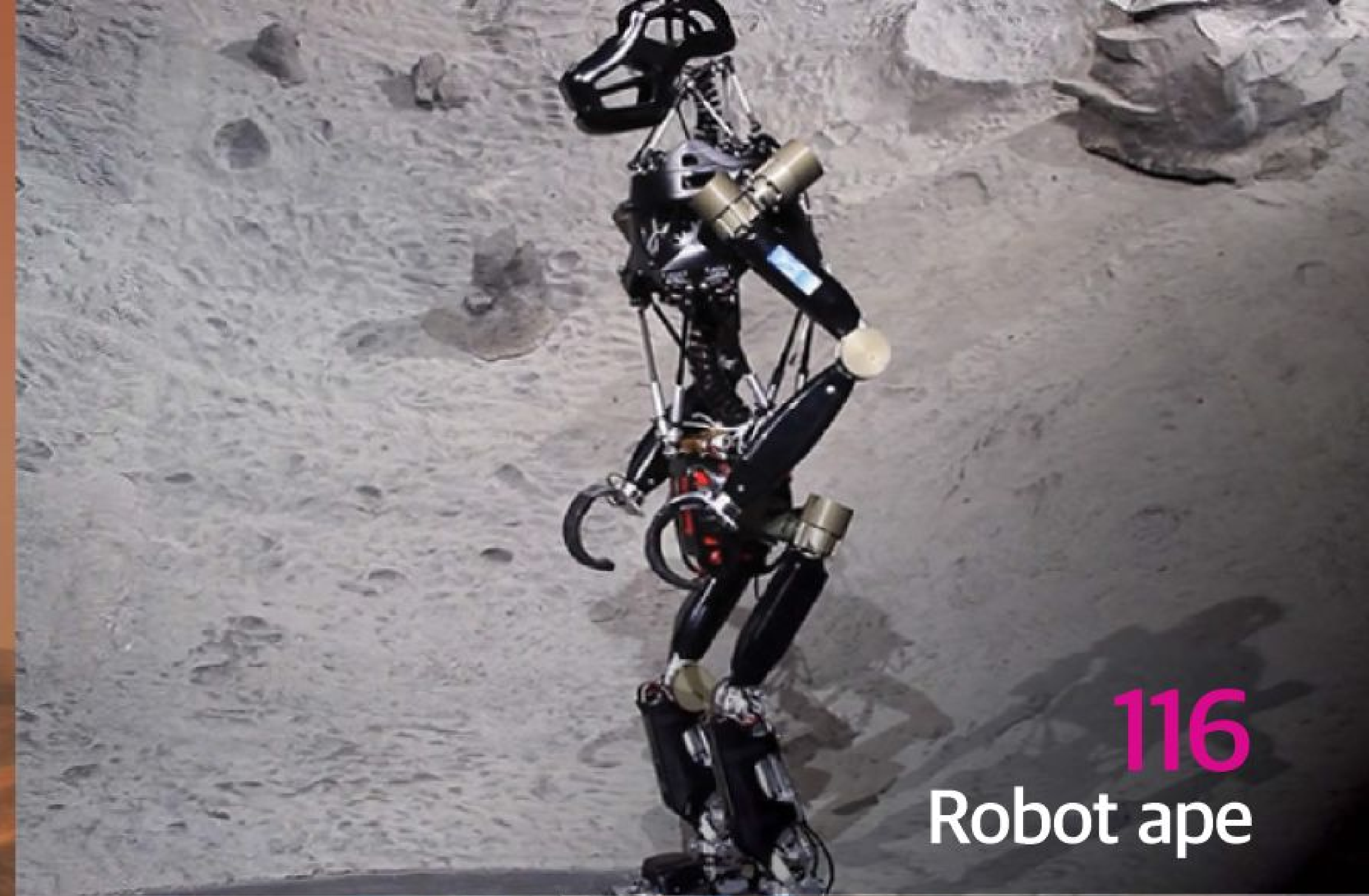


25 SPACE INNOVATIONS

The groundbreaking technologies that will revolutionise how we explore the cosmos

As our ambitions for exploring space become greater, so too do our technological needs. Our current technologies and methods place limits on what we can do, limits that we are starting to press upon as more daring and exciting missions are devised.

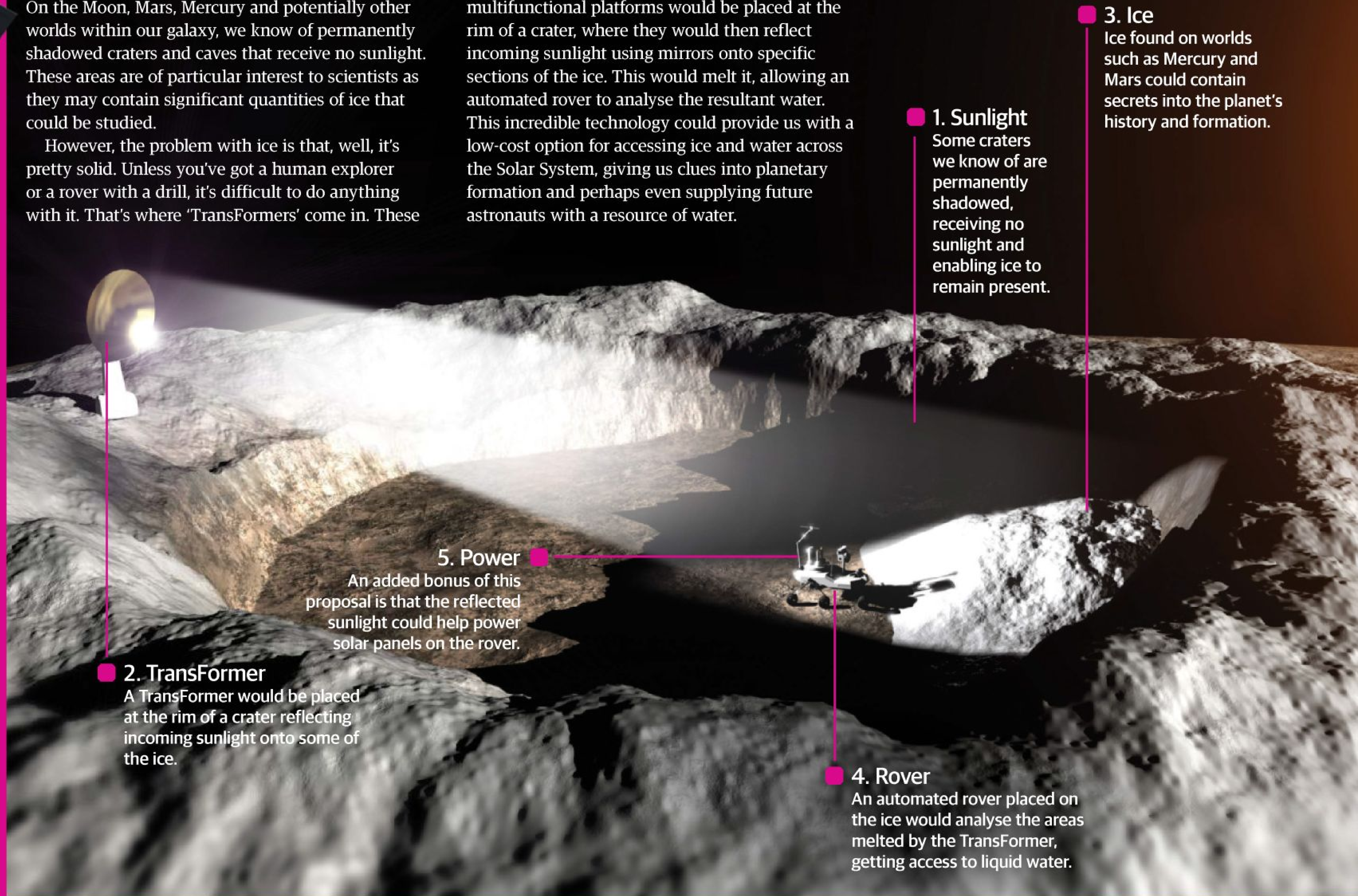
To fulfil our grander ambitions, a variety of companies and agencies are carrying out the research and development that will provide the new technologies we need – from advanced propulsion techniques to reusable rockets.

With that in mind we've chosen 25 technologies that we think could revolutionise our methods of exploring and understanding the universe around us. Some are proposals we'd expect to see in the next few years, others are wholly more ambitious concepts. So, join us as we unveil the incredible future space technologies that will change our methods of space exploration and observation forever.

1 Environment transformers

On the Moon, Mars, Mercury and potentially other worlds within our galaxy, we know of permanently shadowed craters and caves that receive no sunlight. These areas are of particular interest to scientists as they may contain significant quantities of ice that could be studied.

However, the problem with ice is that, well, it's pretty solid. Unless you've got a human explorer or a rover with a drill, it's difficult to do anything with it. That's where 'TransFormers' come in. These multifunctional platforms would be placed at the rim of a crater, where they would then reflect incoming sunlight using mirrors onto specific sections of the ice. This would melt it, allowing an automated rover to analyse the resultant water. This incredible technology could provide us with a low-cost option for accessing ice and water across the Solar System, giving us clues into planetary formation and perhaps even supplying future astronauts with a resource of water.



2 Neutron star explorer

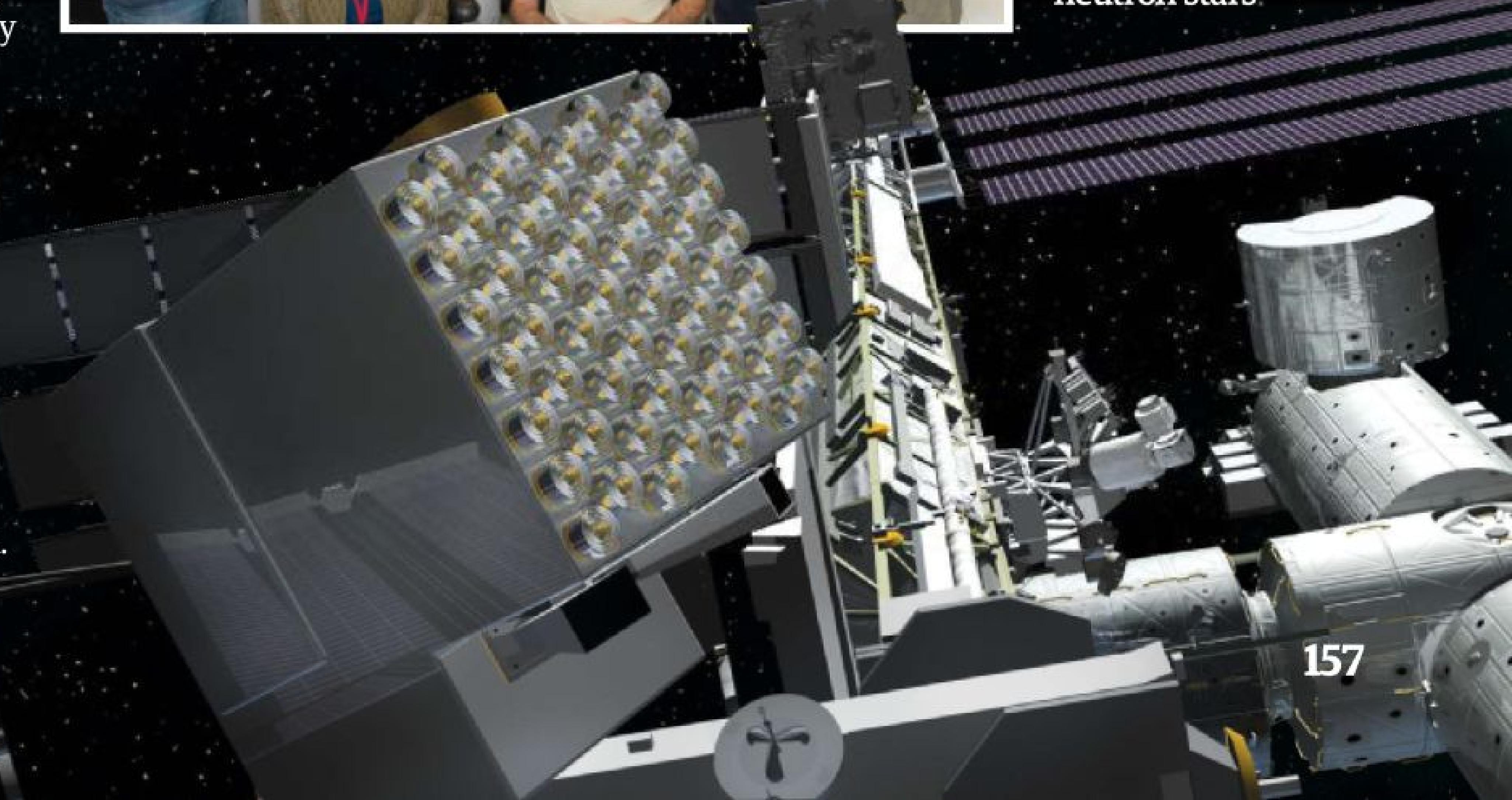
The Neutron star Interior Composition ExploreR (NICER) is a proposed NASA mission that would observe the exotic states of matter within neutron stars.

Our current understanding of neutron stars is good, but it is not complete. We know they are the remnants of stars that have gone supernova, but we are still not quite sure what goes on inside these small but massively dense stars. Most have a radius of just a dozen or so kilometres but contain more mass than 460,000 Earths, making for some fascinating conditions not found anywhere else in the universe.

NICER will allow us to study the emissions of neutron stars and therefore probe their interior structures. Launching in December 2016, NICER will use an X-ray timing and spectroscopy instrument to study these so-called 'undead stars'.

The mission will last 18 months, using 56 mini-telescopes to collect X-rays both from the surfaces of neutron stars and their magnetic fields. For the first time NICER will allow us to accurately measure the size of neutron stars, providing us with key information as to their structure and composition.

Left: The NICER team were named 'Innovators of the Year' by NASA's Goddard Space Flight Center in 2012 for their research and development



Below: NICER will be attached to the side of the ISS away from Earth to enable it to observe neutron stars

3 Deep space CubeSats

CubeSats are tiny spacecraft, often a cube with sides measuring ten centimetres (3.9 inches) in length, that have been used exclusively in Earth orbit for minor experiments such as environmental science.

However, a recent study has suggested that if a suitable form of propulsion can be found, these same mini-spacecraft could be used to explore the far reaches of the Solar System for minimal cost. The problem, as you might expect, is finding that form of propulsion but we might be close to a solution.

Using a dual-mode propulsion system, combining electric and thermal propulsion, could provide the longevity of the former and the high thrust of the latter. Thermal propulsion is excellent for escaping Earth orbit, while electric propulsion is just the ticket for interplanetary travel. Expect more from this promising technology in the future.

"These mini-spacecraft could explore the far reaches of the Solar System"

Made In Space hopes its 3D printer will be used aboard the ISS to produce spare parts

4 Bioprinting in 3D

We all know about 3D printing – using available materials to build something new – but what if you could actually create something out of thin air? 3D bioprinting proposes to do just that. It would be printing on the smallest of scales, using cells drawn from the air and environment to be recomposed into pretty much anything, from food to tools.

Such a technology has one particularly exciting application, namely that it wouldn't require specific things to be fed into it, but rather it reconstitutes the cells of available matter into useful objects. Therefore, it would be the ultimate device for human exploration elsewhere in the Solar System, allowing them to create the supplies they needed from their environment instead of bringing them along for the ride.

5 Tiny robots on Titan

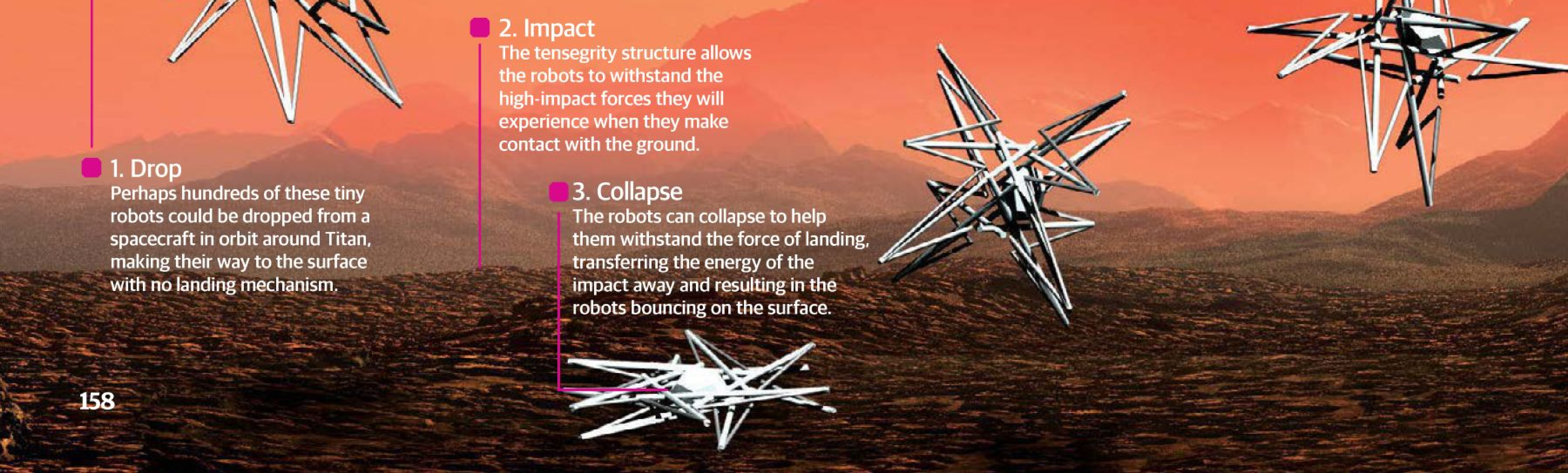
Of all the technology we've focused on in this feature, this is probably one of our favourites. Landing on other worlds has always been a struggle. You have to contend with gravity and possibly an atmosphere as you make your way to the surface, often employing complex and sophisticated landing mechanisms that are not only costly but also risky.

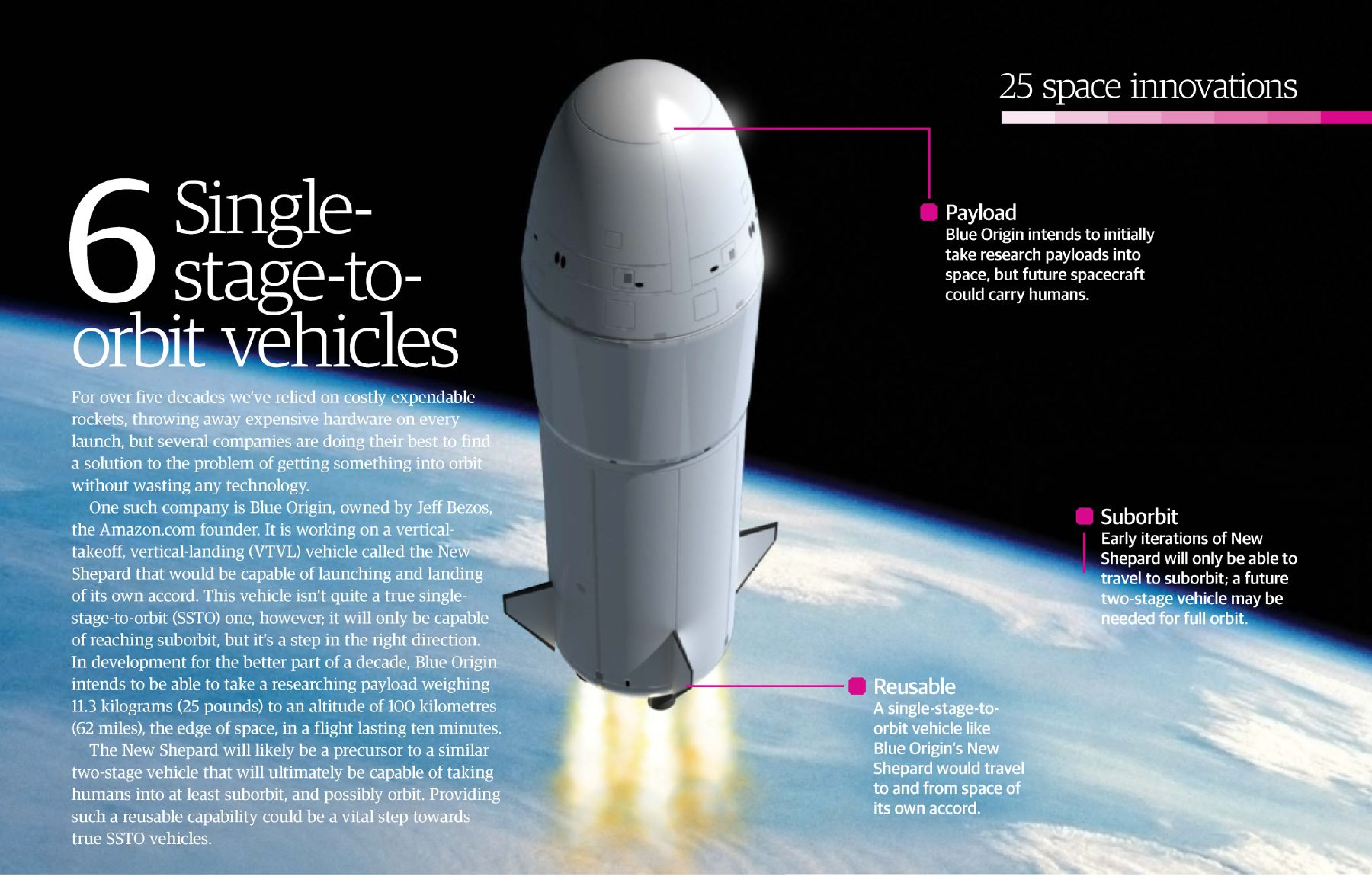
Apparently, though, when a team at NASA made a tensegrity structure like the one in our illustration they accidentally dropped it on the floor and it survived, intact. They wondered: could the same sort of structure be dropped on to the surface of another world without needing to use parachutes or rockets to lower it to the surface? The answer is, well, probably yes.

Small and low-cost missions are going to be increasingly important as we move forward in our space exploration endeavours. This particular idea involves using tensegrity structures, ones with interlocking tubes that create a net tension across the entire structure, to land on another world such as Titan without the need for an additional landing mechanism. By being dropped from a spacecraft in orbit or flying past Titan, the structures could be left to fall through the atmosphere and land on the ground, ready to perform experiments with no mission-ending damage.

Tens or perhaps hundreds of these small machines could be packed into a spacecraft for distribution at Titan. Each could contain different experiments ranging from cameras to environmental sensors, while the machines would also be collapsible, allowing them to get direct analysis of the ground.

It's an ambitious proposal but it's one that seems to be entirely possible. And it's not just Titan these could be used on; the high-impact absorption of these robots means they could also be employed pretty much anywhere in the Solar System.



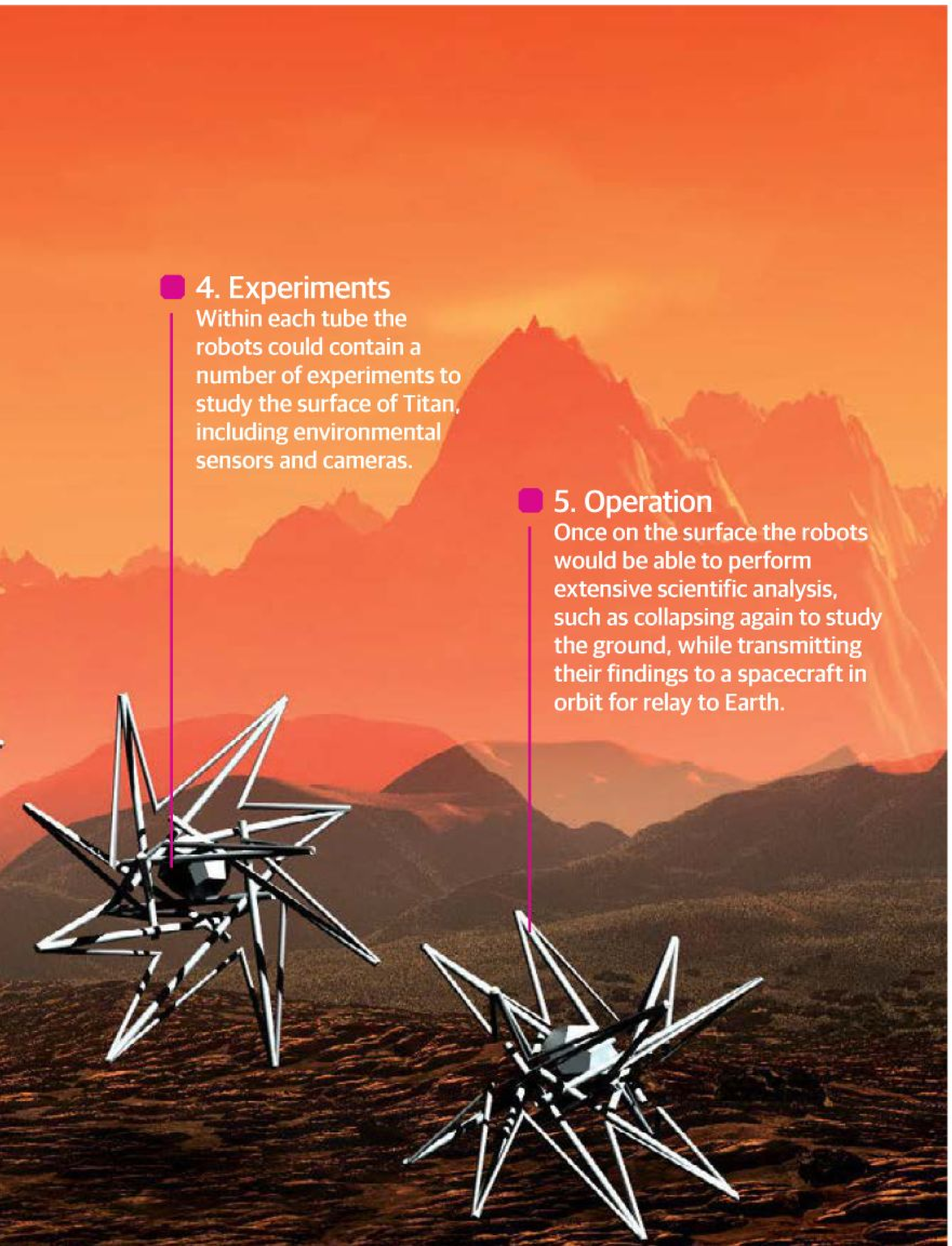


6 Single-stage-to-orbit vehicles

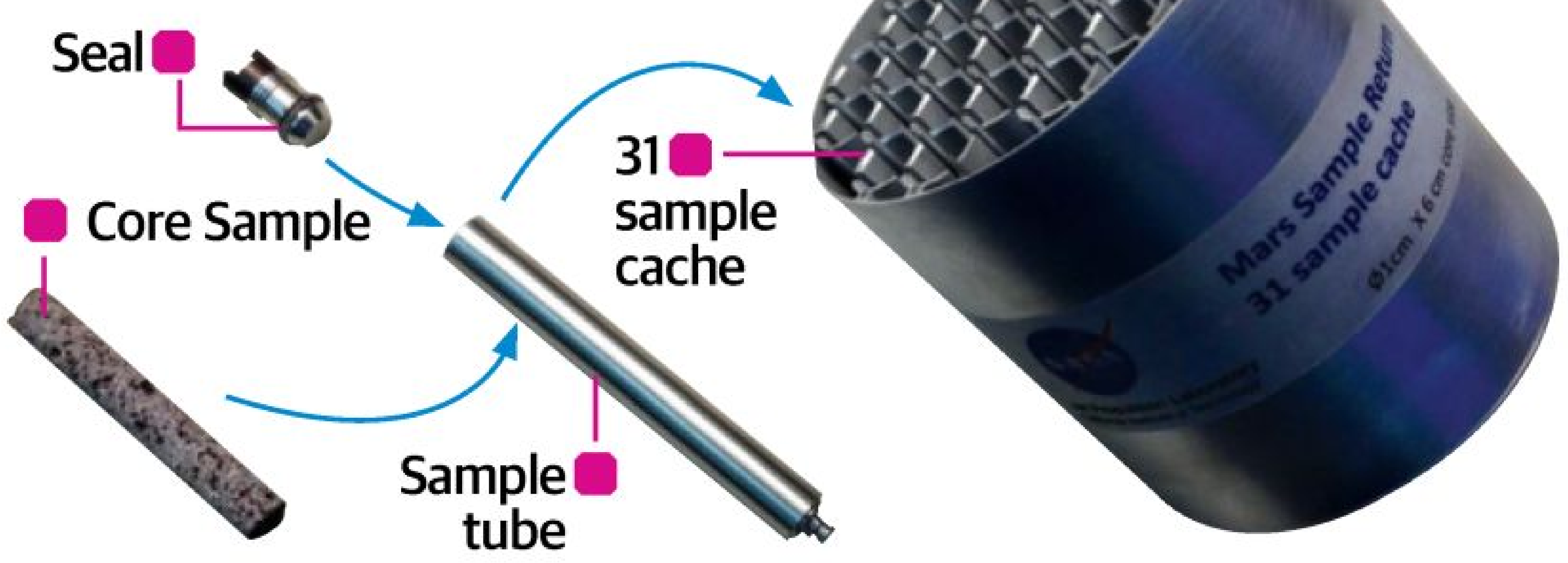
For over five decades we've relied on costly expendable rockets, throwing away expensive hardware on every launch, but several companies are doing their best to find a solution to the problem of getting something into orbit without wasting any technology.

One such company is Blue Origin, owned by Jeff Bezos, the Amazon.com founder. It is working on a vertical-takeoff, vertical-landing (VTVL) vehicle called the New Shepard that would be capable of launching and landing of its own accord. This vehicle isn't quite a true single-stage-to-orbit (SSTO) one, however; it will only be capable of reaching suborbit, but it's a step in the right direction. In development for the better part of a decade, Blue Origin intends to be able to take a researching payload weighing 11.3 kilograms (25 pounds) to an altitude of 100 kilometres (62 miles), the edge of space, in a flight lasting ten minutes.

The New Shepard will likely be a precursor to a similar two-stage vehicle that will ultimately be capable of taking humans into at least suborbit, and possibly orbit. Providing such a reusable capability could be a vital step towards true SSTO vehicles.



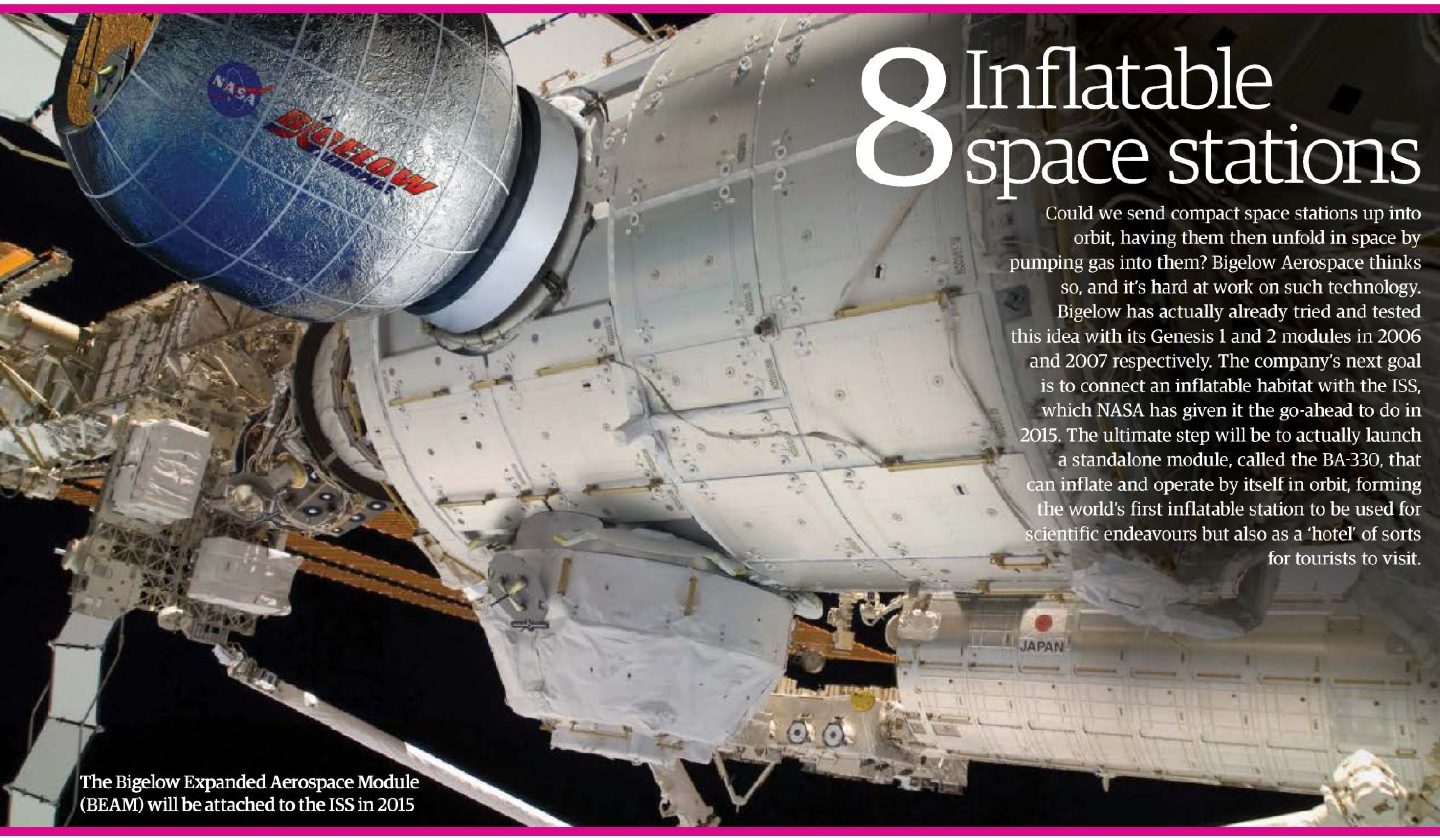
7 Mars sample return mission



NASA's next Mars rover, provisionally named the 2020 Mars Rover, may carry with it a way to collect samples on the surface of Mars for a future robotic spacecraft to collect. Sample return from Mars is a big deal as bringing samples back to be studied on Earth is the next best thing before humans arrive there.

The 2020 Mars Rover would drill hollow cores into the ground that would fill with Martian soil. 31 of these sealed vials of soil would be placed in a sample cache and left on Mars, which an as yet unplanned future spacecraft would be able to pick up. The benefit of this is that the rover could collect samples from different places on Mars, rather than using a stationary lander to just get a sample from one location. The proposed technology is currently being debated for inclusion on the rover, which would be derived from the Curiosity rover and could launch as early as April 2018.

"Sample return from Mars is a big deal for scientists"



8 Inflatable space stations

Could we send compact space stations up into orbit, having them then unfold in space by pumping gas into them? Bigelow Aerospace thinks so, and it's hard at work on such technology. Bigelow has actually already tried and tested this idea with its Genesis 1 and 2 modules in 2006 and 2007 respectively. The company's next goal is to connect an inflatable habitat with the ISS, which NASA has given it the go-ahead to do in 2015. The ultimate step will be to actually launch a standalone module, called the BA-330, that can inflate and operate by itself in orbit, forming the world's first inflatable station to be used for scientific endeavours but also as a 'hotel' of sorts for tourists to visit.

The Bigelow Expanded Aerospace Module (BEAM) will be attached to the ISS in 2015

9 Reusable rockets

Earlier we discussed SSTO vehicles but some are convinced that regular three-stage rockets can be made reusable. One such company with that belief is SpaceX, who is hard at work on its reusable rocket technology called Grasshopper.

Its plan is to use small thrusters on each stage of a rocket to return it under controlled descent back to where it launched from. With its Grasshopper technology SpaceX has already proven that it can raise a rocket several hundred metres off the ground and return it safely to Earth. The next step will be to successfully employ the technology on a fully fledged launch of one of its Falcon 9 rockets, which it expects to do by mid-2014 at the earliest.

SpaceX's Grasshopper completed a number of successful test flights in 2013

LaserMotive, pictured, won the Space Elevator Games with its wirelessly powered climbing robot in 2009

10 Space elevator

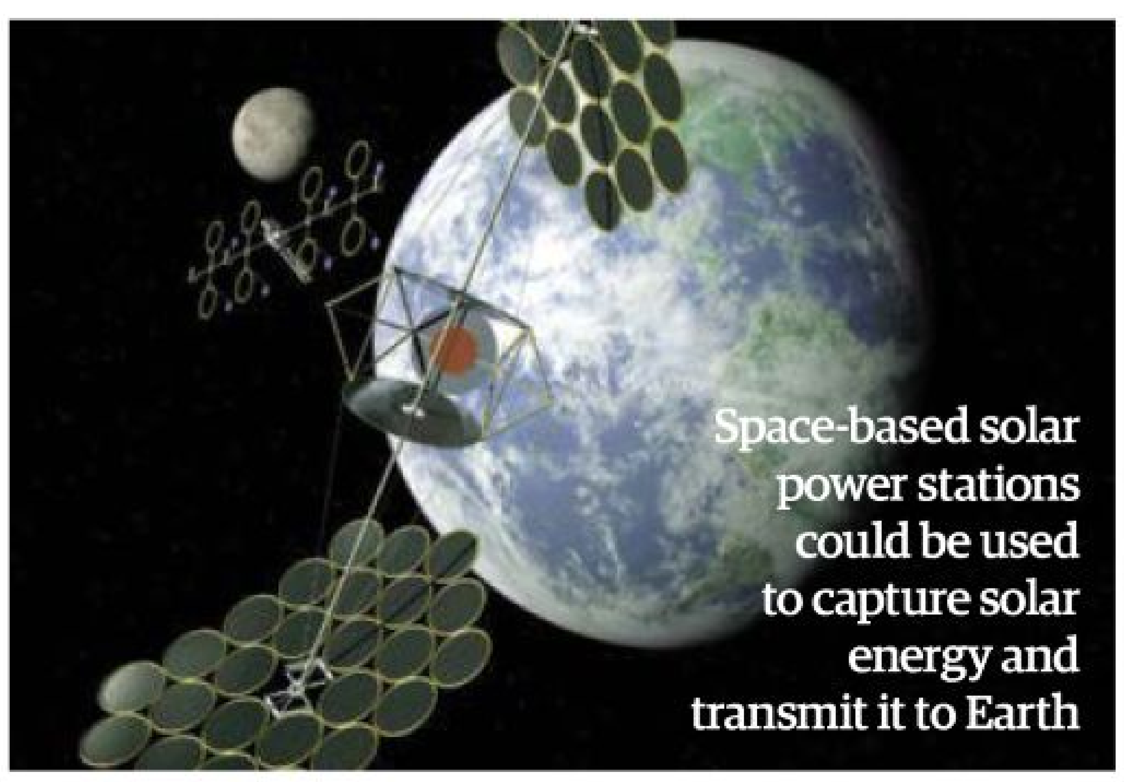
For the last few years NASA has held an annual competition for teams to test out their ability to build strong tethers capable of supporting a 'space elevator' that would enable us to transfer cargo and people to and from orbit without rockets, while also testing out the feasibility of using wireless power transmission to power climbers as they make their way up tethers.

Two things are currently lacking for space elevators; a material strong enough for the cable, and a means of climbing the cable. The former is not too close to being solved, but several teams have shown ways of beating the latter by wirelessly transmitting power to slowly climbing vehicles up a hanging cable. A true space elevator reaching orbit would be a huge contraption; it would need a stable base in low Earth orbit, and a counterweight tens of thousands of kilometres further to keep it in position above Earth.

11 Wireless power transfer

For a while now people have been toying with the idea of wirelessly transferring power to and from space to power spacecraft or harness solar energy from space-based solar farms respectively.

Doing so isn't easy, however. In fact, the world record for wireless power transmission was set way back in 1975 by NASA, who successfully transmitted 34 kilowatts of electrical power a distance of 1.5 kilometres (0.9 miles) at an efficiency of 82 per cent. Using a powerful laser it could be possible to replicate such results to a spacecraft, but doing so will require significant advances in technology. Likewise, microwave transmission has been touted as a possible solution. There are several teams around the world researching such methods, and we'd expect a breakthrough in the next few years.



Space-based solar power stations could be used to capture solar energy and transmit it to Earth

12 In-orbit assembly

To become a true spacefaring civilisation we will need to learn how to construct spacecraft in space rather than launching them from Earth. With that in mind, aerospace company Tethers Unlimited has proposed a new technology called SpiderFab that will be able to build structures in orbit from materials fed into the machine.

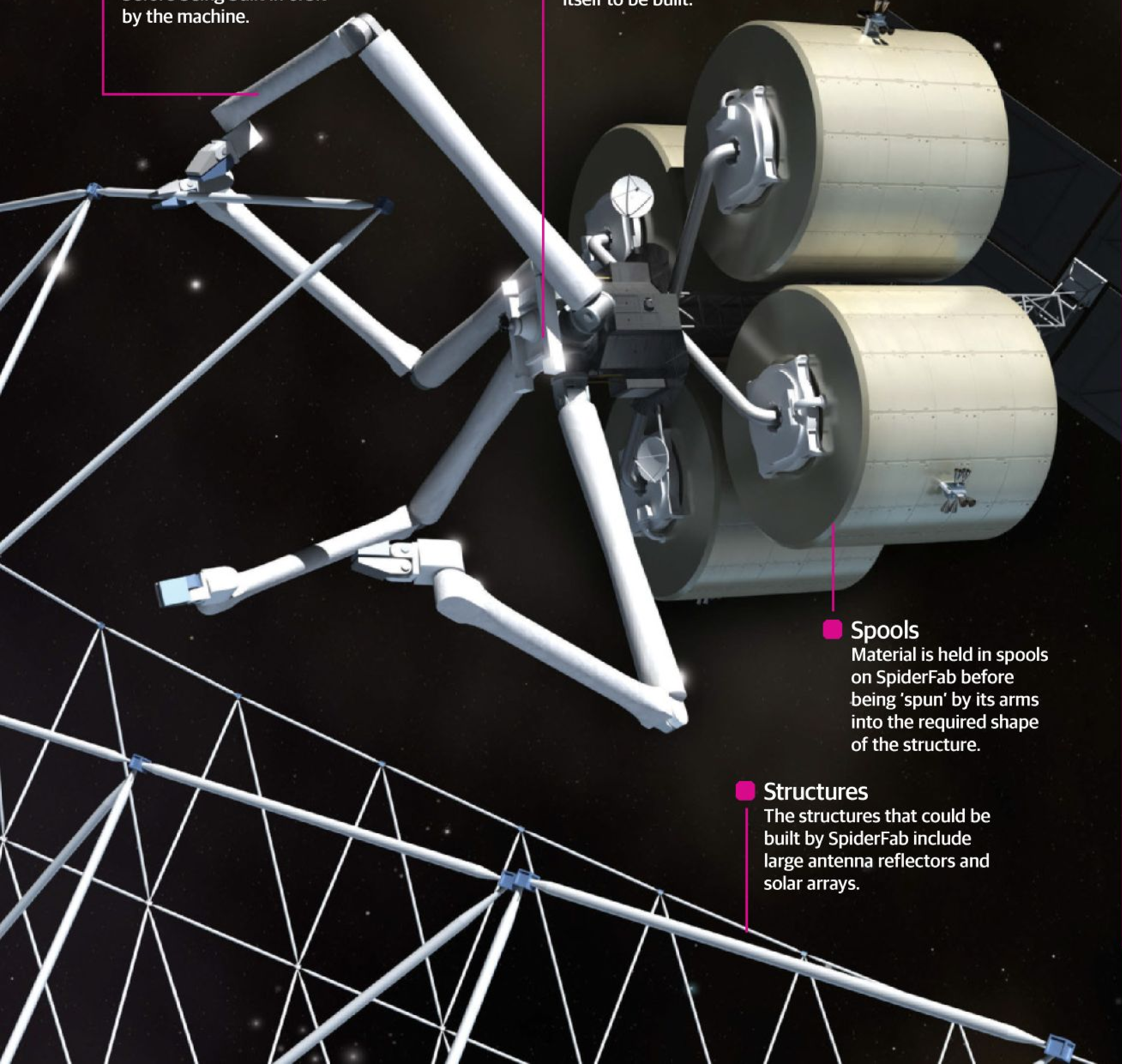
SpiderFab would be launched into orbit by a rocket and, once there, it would use spools of material (most likely carbon fibre) to assemble huge structures. The material is fed from the spools to a 3D printer, which turns the material into a 'web' of sorts that the arms can then contort into the required structure. This could be a variety of things including a support structure for a solar array or the backbone of a large telescope. If successful, such a technology would be revolutionary; it would allow us to build structures in space as opposed to launching them fully complete from Earth.

With the necessary funding, SpiderFab could be ready for a small demonstration within five years. A prototype known as the 'Trusselator' that will use spools of carbon fibre to make high-performance composite trusses is nearing completion. The next step will be to build a truss 100 metres (330 feet) long on a nanosatellite to enable advanced radio astronomy missions.

"Such a technology would be revolutionary; it would allow us to build structures in space"

Compact
The use of SpiderFab would enable structures to be launched compactly before being built in orbit by the machine.

3D printing
SpiderFab will use an inside-out 3D printer, allowing structures much larger than the printer itself to be built.



Spools
Material is held in spools on SpiderFab before being 'spun' by its arms into the required shape of the structure.

Structures
The structures that could be built by SpiderFab include large antenna reflectors and solar arrays.

"SpiderFab – the next step"

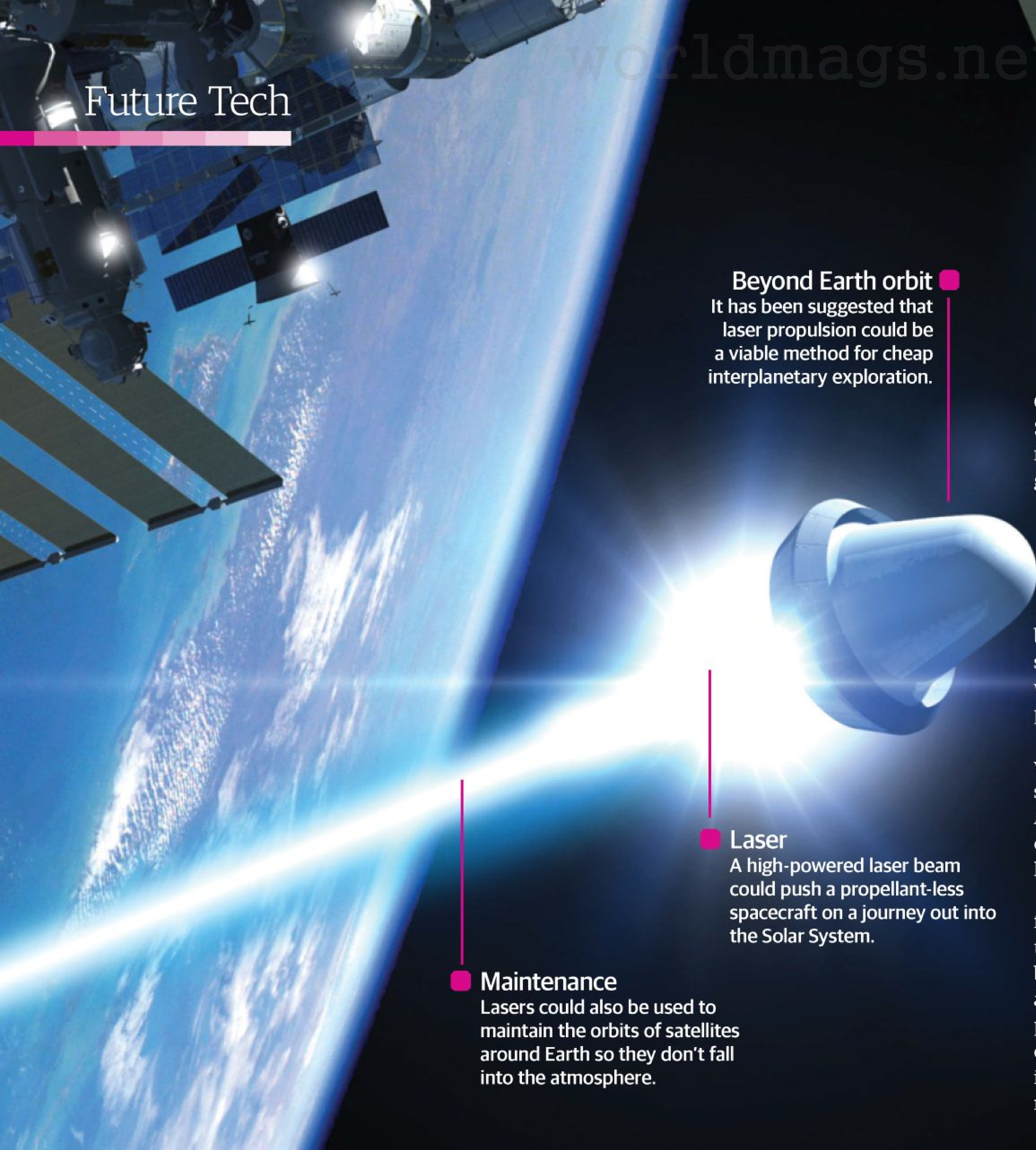
Rob Hoyt, CEO of Tethers Unlimited

Why are technologies like SpiderFab important?
We have taken a big step towards on-orbit construction with the assembly of the ISS, but that assembly was primarily accomplished by bolting together large components prepared on the ground, and required a great deal of expensive astronaut labour. We need to take the next step in advancing on-orbit construction technologies to achieve the potential cost savings offered by on-orbit fabrication.

How does SpiderFab work?
We are currently developing technologies and processes to fabricate support structures for components such as large antennas and solar arrays on orbit. The processes we are developing combine elements of 3D printing, automated composite layup and robotic assembly.

What makes SpiderFab unique?
While a number of prior efforts have looked at on-orbit assembly of systems using components fabricated on the ground, SpiderFab is the first to put all of the necessary steps together to enable a significant portion of a spacecraft to be launched as raw material and then transformed on orbit.

Is this a precursor to building entire spacecraft in orbit?
Theoretically, it should eventually be feasible to fabricate all the components of a spacecraft in orbit, including electronics, optics, solar cells, and so on. I expect that for the foreseeable future, the optimum approach will be to prepare avionics, payloads, and other 'dense' components on the ground, and fabricate on-orbit the components where performance depends upon size.



13 Laser thrusters

One of the biggest limits upon our exploration of the Solar System is fuel. To traverse large distances you either need a lot of fuel, or a clever path that incorporates the gravitational pull of the planets. Carrying large amounts of fuel comes at a cost, and not just a financial one; it also restricts how much useful payload you can take, such as scientific instruments.

So it has long been desirable to build a spacecraft that can be pushed by a new form of propulsion that breaks the limits of what is currently possible. One such solution might be a recent NASA proposal that suggests we could build propellant-less spacecraft pushed along by photons or lasers.

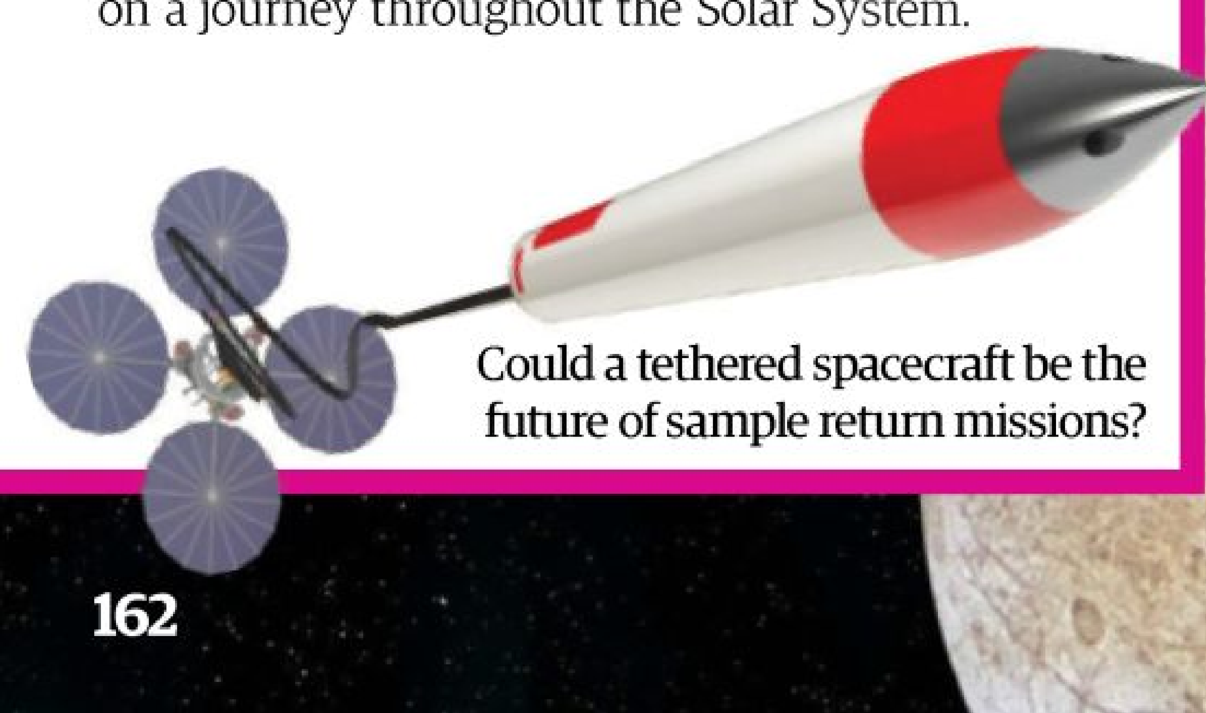
The technology is very much in its infancy, but it's very intriguing nonetheless. One concept could see a solar array in Earth orbit direct photons onto a spacecraft. A 100kW solar panel would produce up to one Newton of constant photon thrust on a spacecraft, accelerating it to high speeds.

Another proposal is to use a high-powered laser beam, fired either from the surface of Earth or from orbit, onto the spacecraft. This provides considerably less of a push but it can more easily be directed onto the spacecraft, allowing for more precise changes in its path. If this particular proposal is followed up, it is expected that a demonstration could be completed between two satellites in Earth orbit within the next three to five years of research and development.

14 High-impact sample return

Since the Apollo missions just a handful of spacecraft have returned samples to Earth. Getting samples from a body back to Earth can be a costly and risky endeavour, but one proposal to NASA has devised a way to do just that with a simple and effective spacecraft.

This sample return system for extreme environments would involve the use of a spacecraft attached to a sample capsule on a tether. Upon approach to a body the spacecraft fires its thrusters to spin before flinging the sample capsule, at the end of the tether, towards a nearby body. The capsule impacts at high speed, possibly travelling over a metre (3.3 feet) beneath the surface. The sample can then be drawn back to the spacecraft on the tether or collected from a suborbital launch. This method would allow multiple samples to be taken from multiple bodies on a journey throughout the Solar System.



Could a tethered spacecraft be the future of sample return missions?

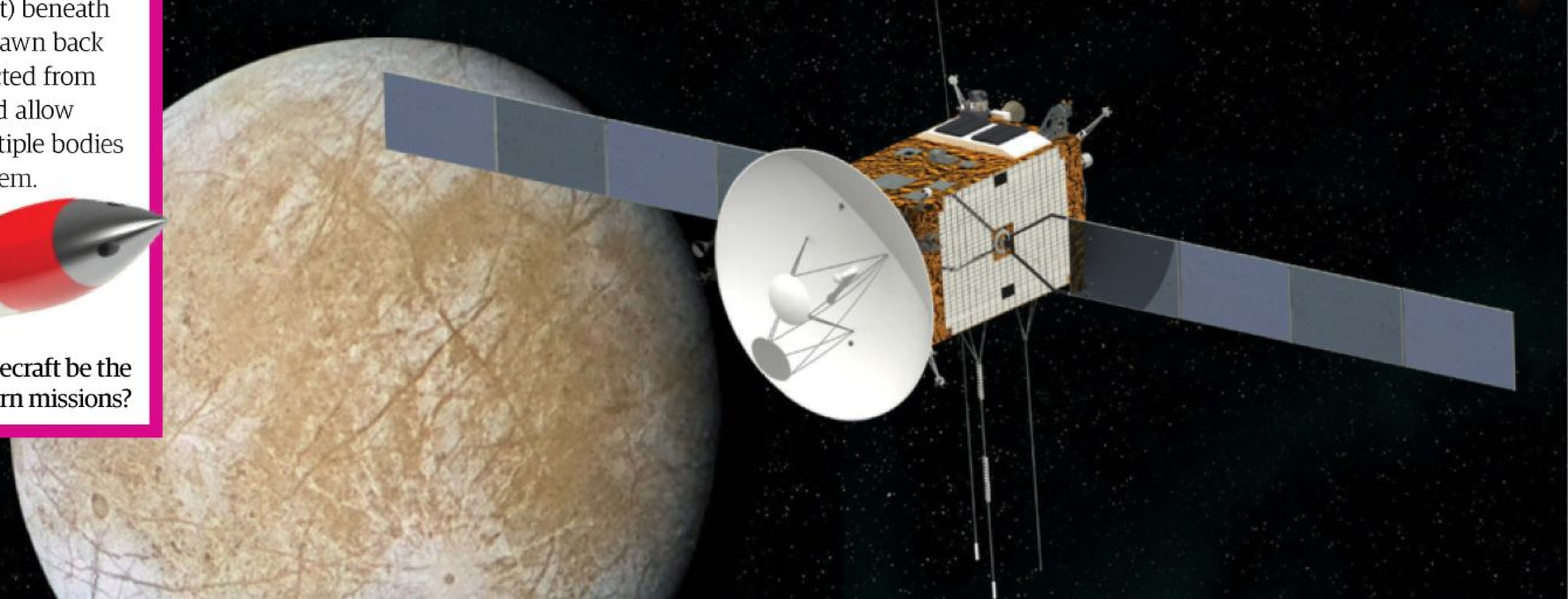
15 Measuring Europa's crust

In 2022, the ESA will launch its first mission to Jupiter, the JUpiter ICy moons Explorer (JUICE), which, as its name suggests, will be tasked with studying the gas giant and its fascinating moons.

One of the most intriguing instruments aboard JUICE will be its ice penetrating radar (IPR). Using a method not too dissimilar to sonar employed by submarines, the instrument will be able to make precise measurements of certain moons.

In particular, the IPR will be able to measure the thickness of Europa's icy crust, which in turn will enable us to discern how far underground its subsurface ocean could be. The IPR will also be able to make similar measurements on Callisto and Ganymede, the latter of which is also believed to be hiding an ocean under its frozen surface. If the launch stays on schedule, JUICE will begin its mission in the Jovian system in the early 2030s.

"An overarching theme for JUICE is the emergence of habitable worlds around gas giants" **Dr Dmitri V Titov, ESA JUICE scientist**



16 The Z-1 Spacesuit

If we aim to one day land on Mars, we're going to need a spacesuit that can handle not only the extreme environment of the Red Planet but also the intense radiation that the astronauts will be subjected to. Fortunately, NASA has been working on a suit that will fill the needs of future Martian explorers, dubbed the Z-1 spacesuit.

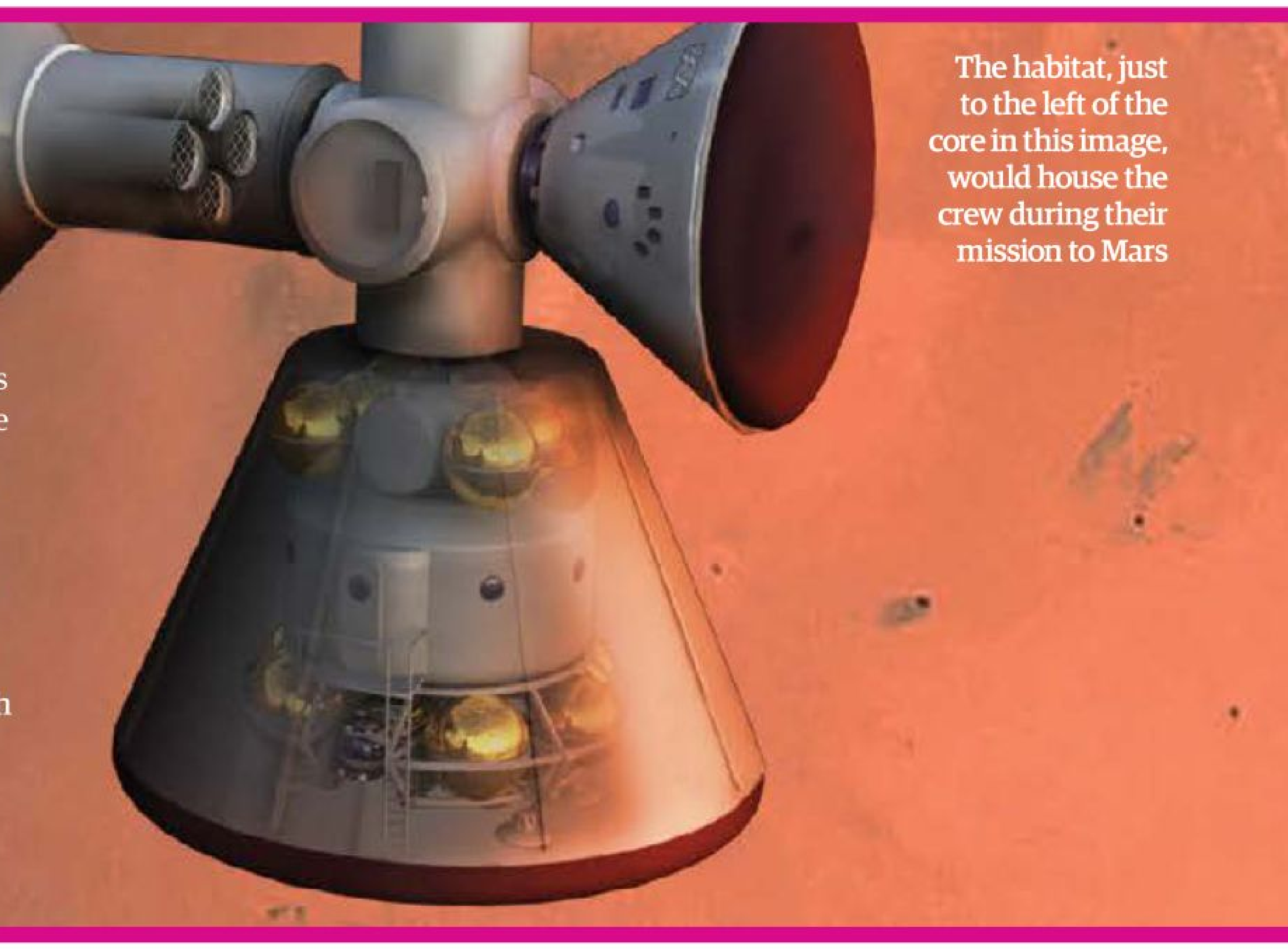
The Z-1 employs a number of innovative design features that will make future Mars missions possible. One of those features is the use of a suitport, which enables astronauts to climb into the suit through a port at the back, a useful concept that means the Z-1 can be attached to the exterior of a spacecraft.

The Z-1 itself is a prototype, but it will be the predecessor to the eventual suit that will be used on the surface of Mars. Many of its technologies and features are likely to be employed on the next spacesuit, provisionally dubbed the Z-2.

17 Stasis habitats

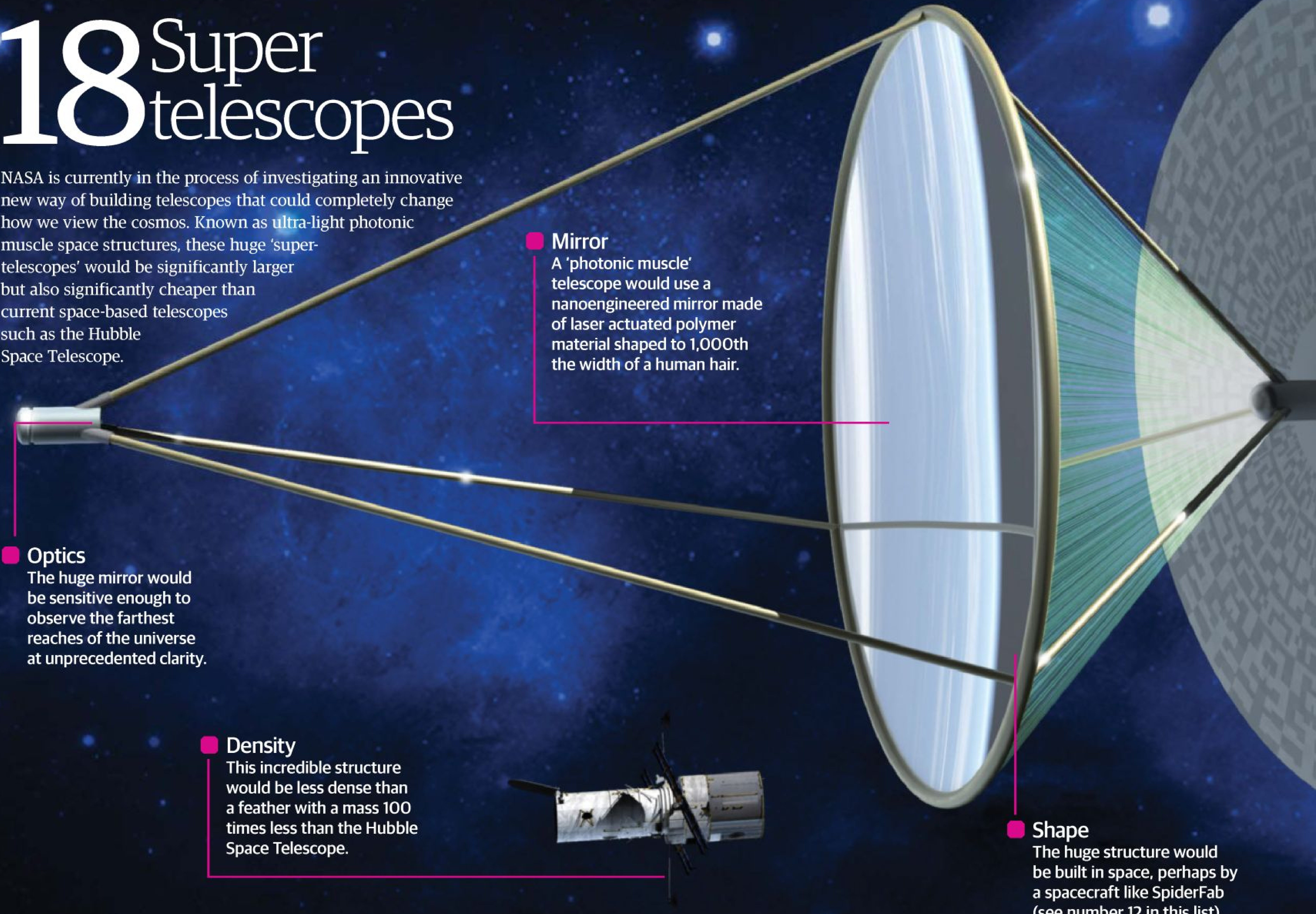
Suspended animation is something you've probably heard of in various works of science fiction, but a concept from aerospace company SpaceWorks Enterprises suggests that it's a plausible technology that is not beyond the realms of imagination.

Recent medical research is slowly enabling us to induce deep sleep in a human being, known as torpor. SpaceWorks suggests that, if such a technology is perfected, we could use a torpor-inducing transfer habitat for a mission to Mars. The benefits of such a system would be that the crew would require minimal supplies and living space on the journey there while in stasis, drastically reducing the size of the spacecraft needed for launch. Upon arrival, they would be woken to begin their mission. There are several problems that must be overcome before such a technology can be considered, including research into the effects of long-term stasis on humans, but if conquered this could be the key for future manned missions into deep space.


The habitat, just to the left of the core in this image, would house the crew during their mission to Mars

18 Super telescopes

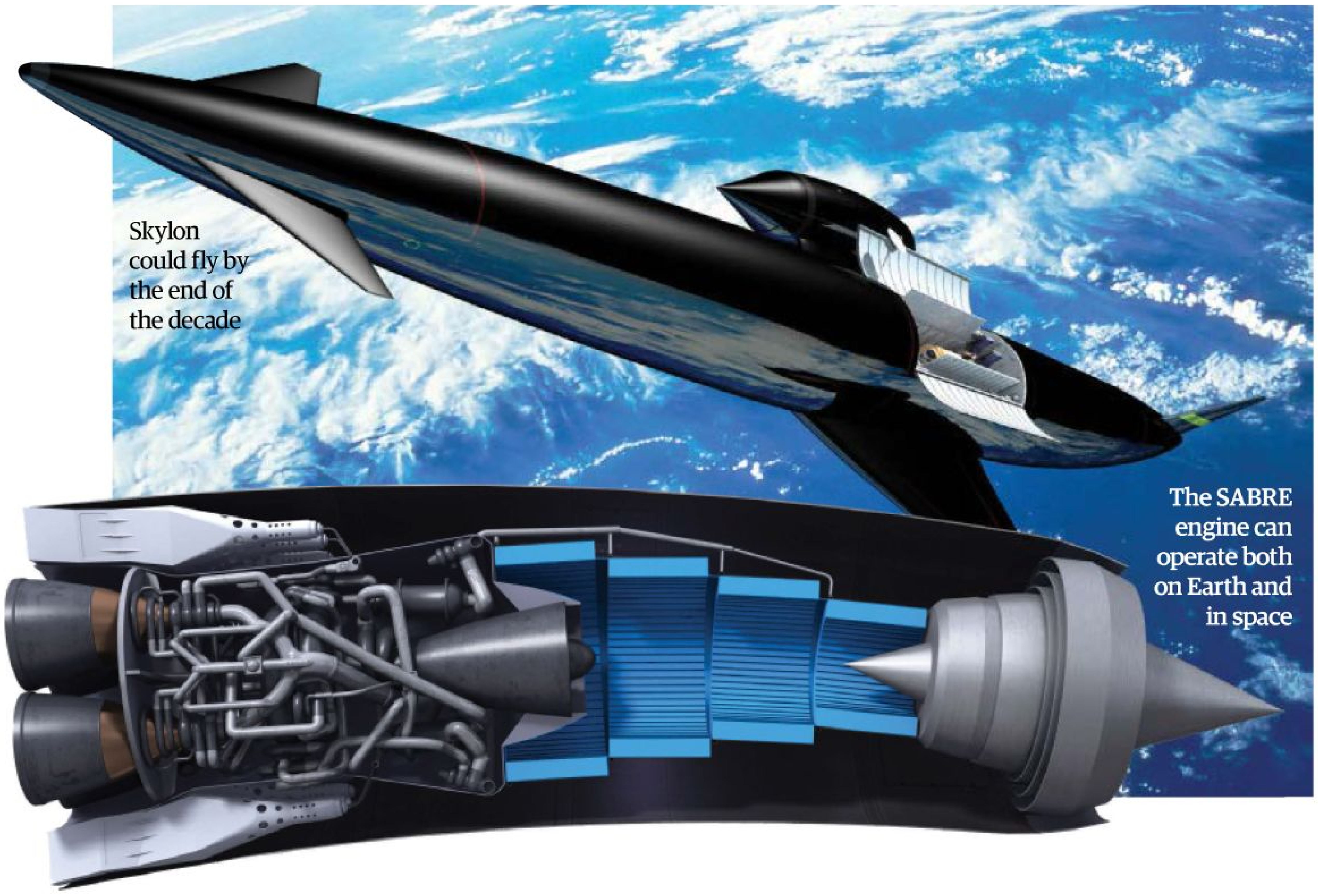
NASA is currently in the process of investigating an innovative new way of building telescopes that could completely change how we view the cosmos. Known as ultra-light photonic muscle space structures, these huge 'super-telescopes' would be significantly larger but also significantly cheaper than current space-based telescopes such as the Hubble Space Telescope.



19 The SABRE engine

One of the problems with building a true spaceplane, one that can launch from a runway into space and return to Earth, is that an engine is needed that can operate both within the atmosphere of Earth and the vacuum of space.

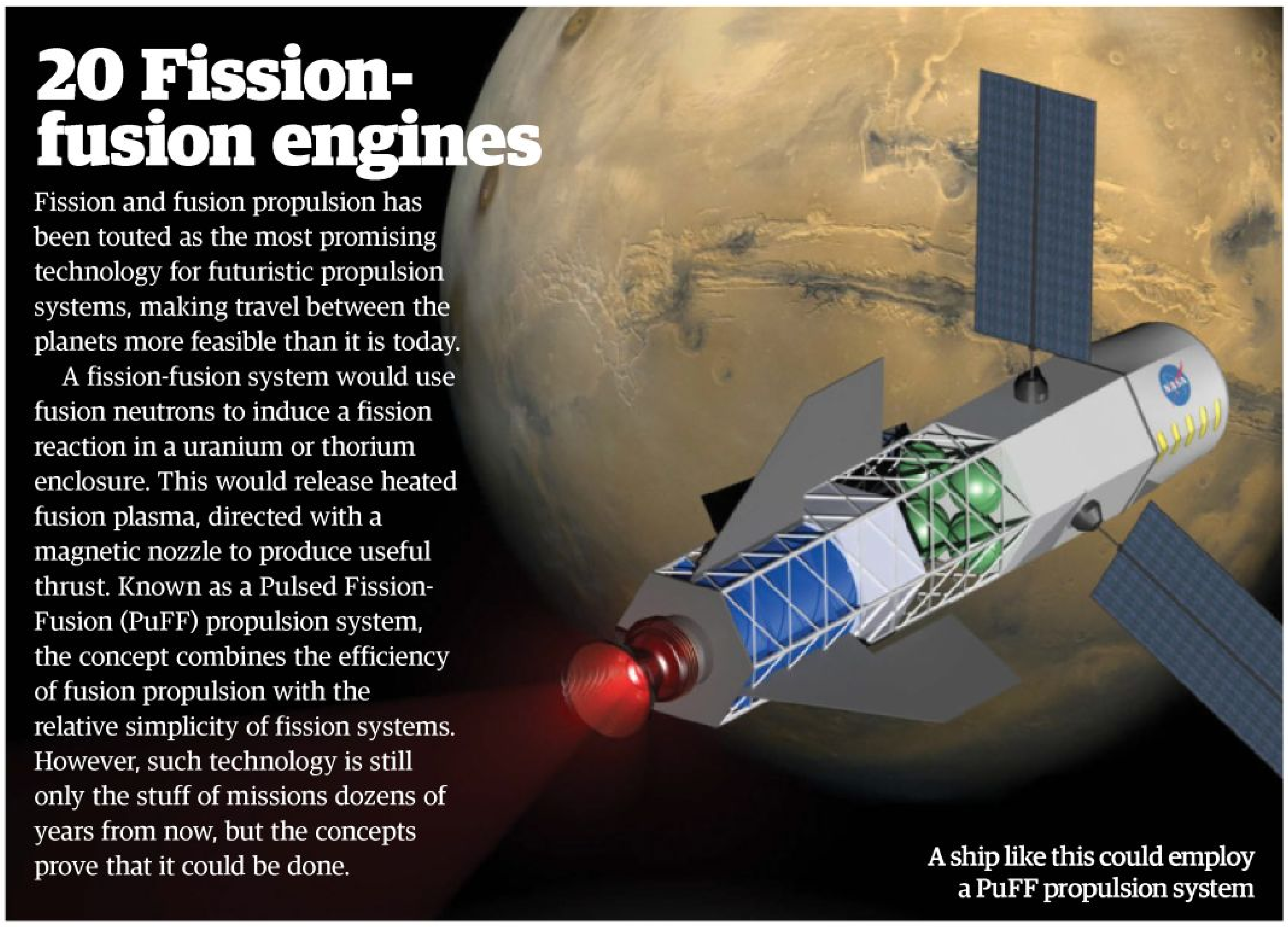
Reaction Engines Limited is currently hard at work on its futuristic spaceplane known as Skylon, which will employ a revolutionary engine known as SABRE that enables the operation of the vehicle in both environments. While taking off from the ground the engine remains in air-breathing mode, drawing in oxygen like a jet engine. When above the atmosphere it enters rocket mode, using on-board liquid oxygen to reach orbital speeds. Components of the engine have already been tested and, if it eventually flies, it could be one of the most significant advancements in spaceplane technology yet.



Skylon could fly by the end of the decade

The SABRE engine can operate both on Earth and in space

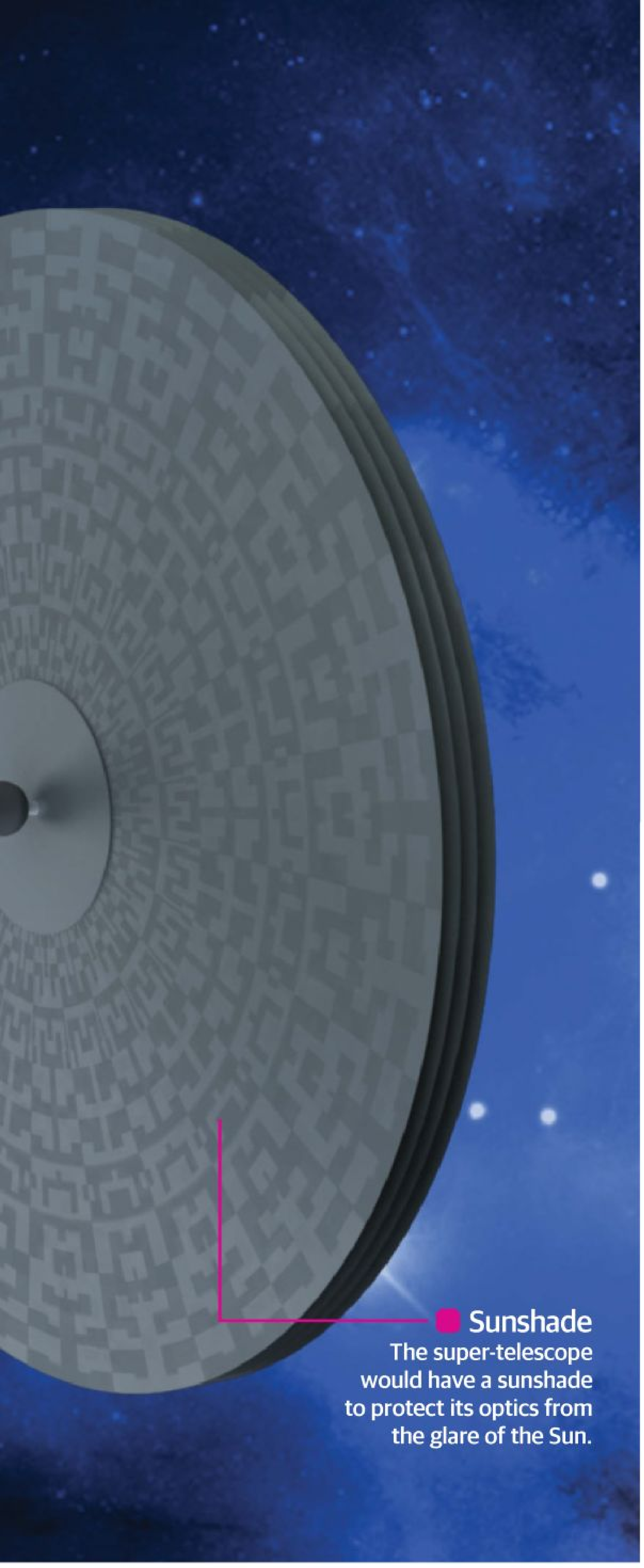
20 Fission-fusion engines



Fission and fusion propulsion has been touted as the most promising technology for futuristic propulsion systems, making travel between the planets more feasible than it is today.

A fission-fusion system would use fusion neutrons to induce a fission reaction in a uranium or thorium enclosure. This would release heated fusion plasma, directed with a magnetic nozzle to produce useful thrust. Known as a Pulsed Fission-Fusion (PuFF) propulsion system, the concept combines the efficiency of fusion propulsion with the relative simplicity of fission systems. However, such technology is still only the stuff of missions dozens of years from now, but the concepts prove that it could be done.

A ship like this could employ a PuFF propulsion system



Sunshade
The super-telescope would have a sunshade to protect its optics from the glare of the Sun.

21 Space radiation protection

Active radiation shielding remains a very significant challenge if humans are to venture past the Moon and deeper into space. It is already known that, beyond the protective regions of Earth's magnetosphere astronauts will be subjected to potentially fatal levels of radiation. Various methods have been touted to overcome this problem, including surrounding the crew's habitat with water or using coiled spacecraft. The former method would use a layer of water in the walls of a spacecraft, perhaps recycled from the astronauts' every day usage, as water is known to be an excellent blocker of radiation. A more ambitious coil structure to the spacecraft, meanwhile, would use a magnetic field to protect the astronauts. While both are yet to be properly tested in space, they are both viable methods that could be employed in future.

Planet
A starshade blocks the light of a star, enabling a telescope to more easily observe planets in orbit.

22 Observing exoplanets

In 2018 NASA's James Webb Space Telescope will launch, the most powerful space telescope humanity has ever built. While it will offer unrivalled views of the cosmos, some scientists have suggested that there are additional features we could use with the JWST to revolutionise the field of astronomy. One of those is to launch a starshade with the telescope. The technology has been around for years, but budget restraints have seen it remain a concept rather than an actual mission. Basically, a giant shade would be used to block the light of a distant star known to harbour exoplanets and a powerful telescope, such as the JWST, would peer just past the shade and be able to directly observe the exoplanets. Such a proposal for a starshade-centric telescope is currently under consideration by NASA for funding in 2015. If picked it could offer a whole new insight into exoplanets.

23 Space habitats

A recent concept proposal to NASA has suggested that the tensegrity structure we discussed earlier for use on Titan could be used to build a space habitat near the Moon, albeit on a far larger scale. The lightweight structure would use water gleaned from space-based materials as a means to provide shielding for its inhabitants. Known as growth adapted tensegrity structures, these could be an excellent way to build large-scale habitats in space.

24 Telerobotics

Time delays make communications during deep space exploration difficult. For example, it takes about 15 minutes to send or receive a message to or from the Curiosity rover on Mars, meaning that any progress is slow. In fact, it is often said that a human could accomplish in a day what the various rovers have accomplished in their combined time on Mars.

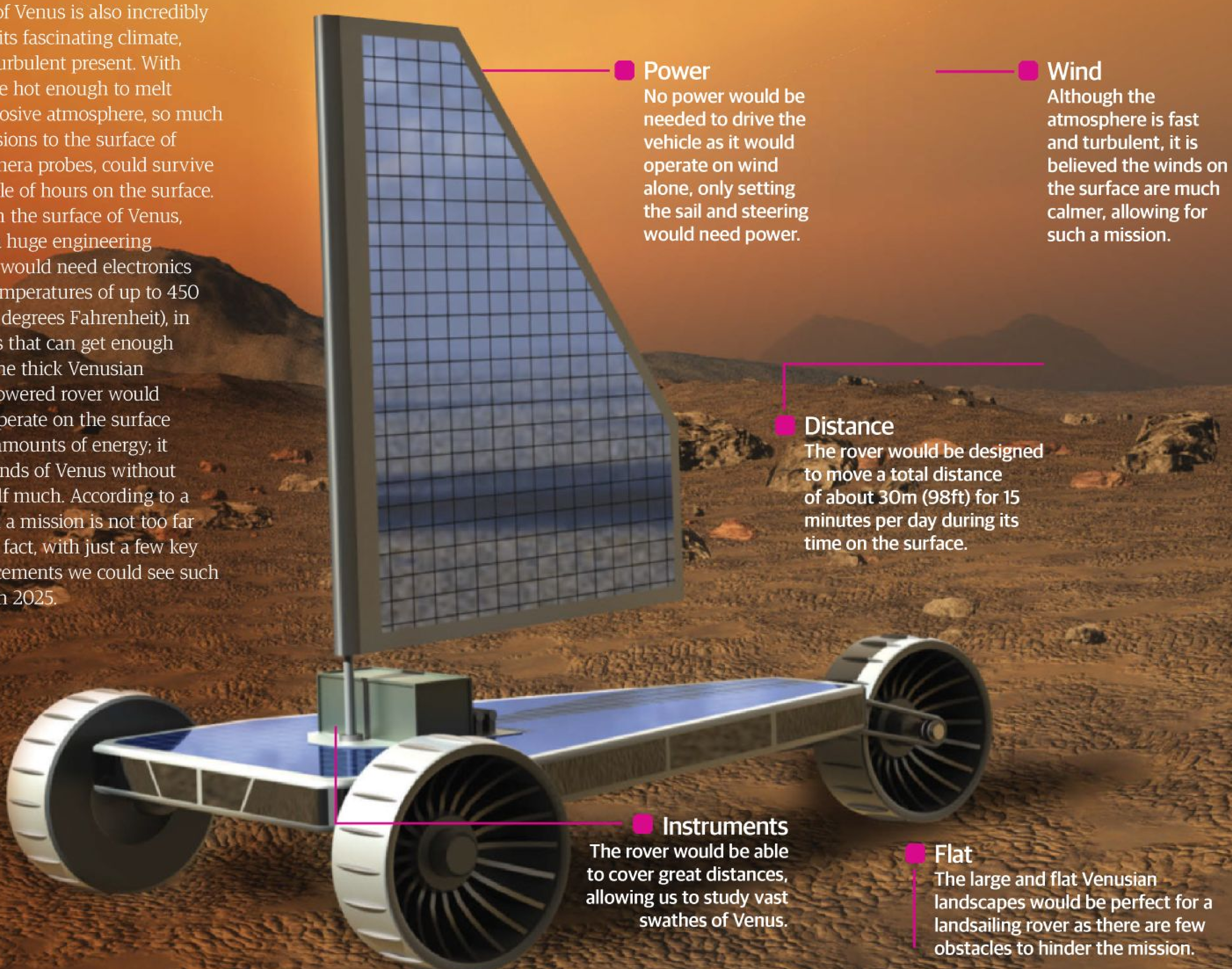
Telerobotics, however, could allow better and faster exploration of other worlds by using astronauts in the vicinity of a rover to remotely control its actions. For example, a team of astronauts on the surface of the Martian moon Phobos could control a rover on the surface of Mars with just a split-second time delay.

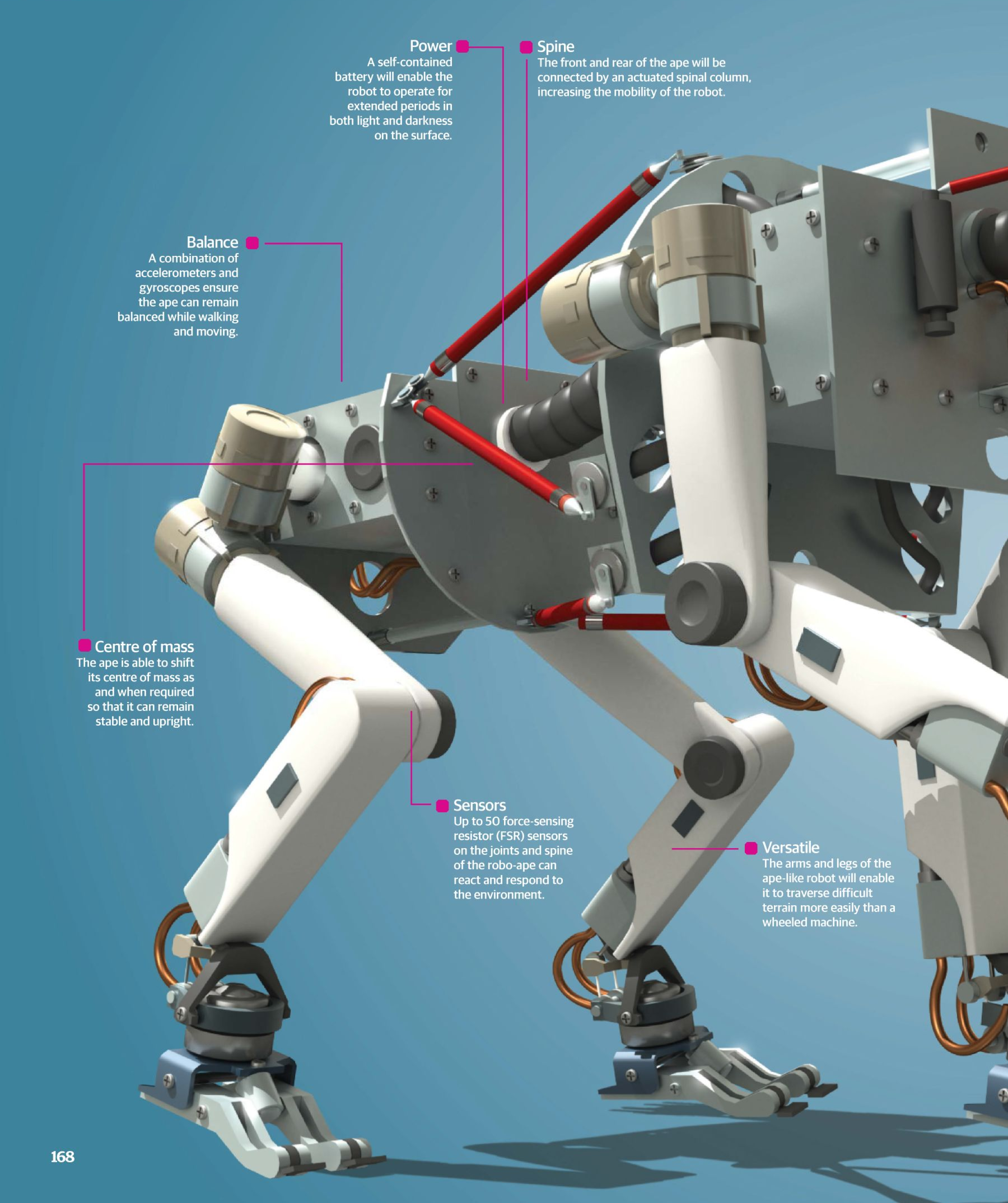
25 Windsailing on Venus

"The rover would need to survive temperatures of up to 450 degrees Celsius"

One of the most hostile places in the Solar System, the surface of Venus is also incredibly intriguing thanks to its fascinating climate, bizarre history and turbulent present. With a surface temperature hot enough to melt spacecraft and a corrosive atmosphere, so much so that our only missions to the surface of Venus, the Soviet Venera probes, could survive no more than a couple of hours on the surface.

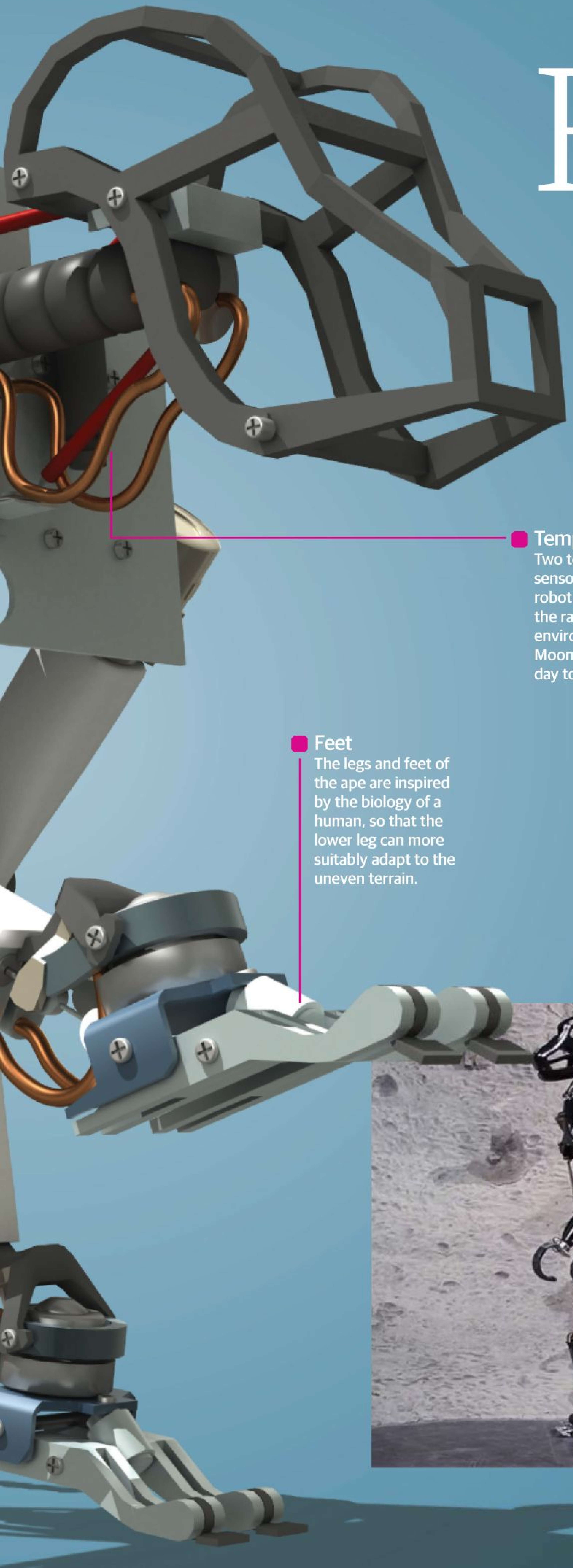
Landing a rover on the surface of Venus, therefore, would be a huge engineering challenge. The rover would need electronics that could survive temperatures of up to 450 degrees Celsius (842 degrees Fahrenheit), in addition to solar cells that can get enough sunlight even with the thick Venusian atmosphere. A sail-powered rover would enable a vehicle to operate on the surface with relatively little amounts of energy; it could drift on the winds of Venus without needing to drive itself much. According to a NASA proposal, such a mission is not too far off being possible. In fact, with just a few key technological advancements we could see such a mission go ahead in 2025.




Power
A self-contained battery will enable the robot to operate for extended periods in both light and darkness on the surface.
Spine
The front and rear of the ape will be connected by an actuated spinal column, increasing the mobility of the robot.
Balance
A combination of accelerometers and gyroscopes ensure the ape can remain balanced while walking and moving.
Centre of mass
The ape is able to shift its centre of mass as and when required so that it can remain stable and upright.
Sensors
Up to 50 force-sensing resistor (FSR) sensors on the joints and spine of the robo-ape can react and respond to the environment.
Versatile
The arms and legs of the ape-like robot will enable it to traverse difficult terrain more easily than a wheeled machine.

Robot ape

Introducing the iStruct Demonstrator, the robo-ape that could one day be clambering across the Moon



The German Research Centre for Artificial Intelligence (DFKI) and the University of Bremen have put together a prototype four-legged robo-ape, known as the iStruct Demonstrator – a machine that will employ several smart innovations to help it traverse the Moon's hills and craters. The benefits of such a proposal largely centre around its manoeuvrability – where a rover may struggle with the slope of a crater or rocks strewn across the ground, a robo-ape could clamber up a slope on all-fours or carefully pick its way over rocks.

Weighing in at 18 kilograms (40 pounds) and with dimensions of 66 x 43 x 75 centimetres (26 x 17 x 30 inches), the robot is similar in both size and stature to real apes, which are well known for their versatility in many environments. Another benefit of the design is that the robot could stand on its hind legs while its hands are used for other purposes.

There are 43 sensors that can detect the force pressed on them when the machine walks, enabling it to remain stable. Six sensors on the exposed sections of the ape are used for collision-detection, distance sensors tell it how far away the ground is as it walks, while a three-axis accelerometer orientates the feet so that steps are taken according to the slope of the ground below.

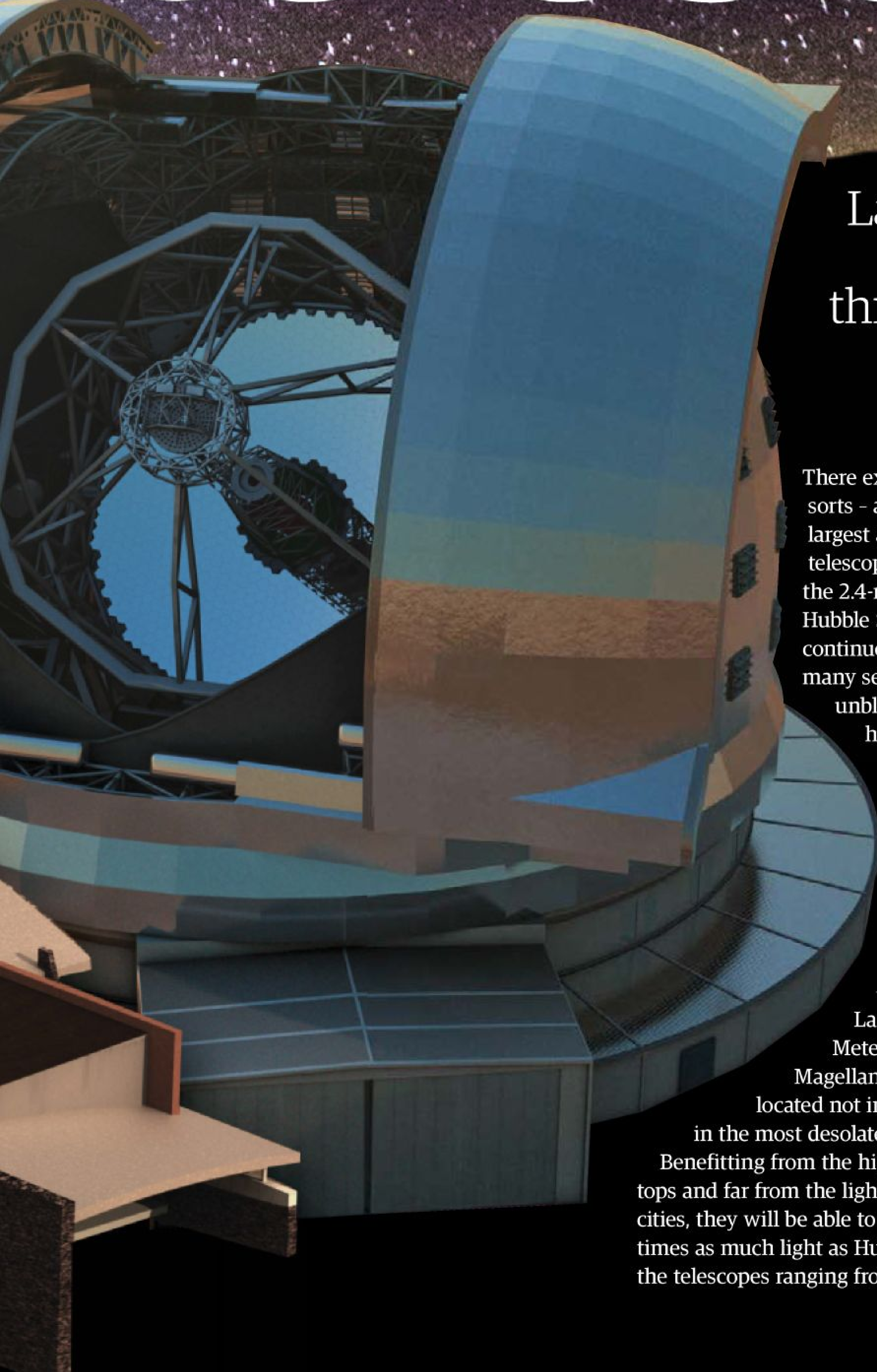
The University of Bremen and DFKI partnership has also incorporated something called a multi-locomotion system. This replaces an otherwise solid and inflexible connection between either end of the iStruct Demonstrator's body with an actuated spinal column. From this flexible core, a six-axis force/torque sensor makes sure the ape doesn't topple over while walking, or performing more-complicated actions when moving around on all four limbs.

Gone would be the slow progress made by a rover, analysing the ground ahead before trundling on. Instead, robo-apes could adeptly pick their way across treacherous terrain to perform key science in alien locales.

While the iStruct Demonstrator is just a prototype for future innovative robot explorers, it's possible that a descendant of this robo-ape could one day visit the Moon or even worlds further afield. Places that could prove too dangerous or simply too expensive for a manned mission could be probed by this relatively cheap piece of technology. With continuing iterations and improvements, descendants of the iStruct could remain on the far side of the Moon. A trip to Mars could even be on the cards, with the robot reacting to its environment and paving the way for a manned mission.


An upright position will free up the robot's hands

Billion-dollar telescopes



Larger than any telescope ever developed and capable of peering deep into space, three expensive super structures are set to change our view of the universe forever

There exists a new space race of sorts – a scramble to create the largest and most sophisticated telescopes ever devised. While the 2.4-metre- (7.9-foot-) aperture Hubble Space Telescope may continue to impress as it reveals many secrets of the universe and unblocks further chunks of human knowledge, the extremely large ground-based telescopes that are on the verge of being built will surpass its achievements many times over.

Each of the next-generation telescopes – the European Extremely Large Telescope, the Thirty Meter Telescope and the Giant Magellan Telescope – will be located not in space, but here on Earth in the most desolate regions.

Benefitting from the high altitudes of mountain tops and far from the light pollution of towns and cities, they will be able to gather more than ten times as much light as Hubble. What's more, with the telescopes ranging from 25 to 39.1 metres (82 to 128 feet) in diameter, these massive observatories will be able to detect atoms and molecules that are several light years away, giving us glimpses of the universe like never before.

These telescopes follow the scientific line set by Galileo and Newton, but are attempting to redefine the rules. In the history of telescope-building, each generation has been roughly twice as large as the previous. The eight- and ten-metre (26- and 33-foot) telescopes we see around today followed four-metre (13-foot) telescopes – they in turn had followed two-metre (6.6-foot) devices.

The drive for new optical technologies has only intensified as the years have rolled by. So, while Jodrell Bank Observatory in the UK heralded the invention of radio-astronomy in Europe in 1945, and the first space telescopes opened up new regions of electromagnetic spectrum, astronomers have wanted to leap ahead quicker than ever before. It's certainly no accident that the E-ELT in particular advances by a factor of four – the team would have gone bigger if they could.

Of course, this is a good thing, and there's no question that larger telescopes are needed – they will satisfy a desire by a huge numbers of scientists to open new frontiers. The only major issue, given the advances that will be made, is whether the world should actually be creating more. But that's a topic of debate for another time.

Europe's window to the universe is extremely large

Set for completion in 2024, the E-ELT Telescope will see with a stunning 15 times the detail of the Hubble Space Telescope

INTERVIEW BIO

Dr Joe Liske
European Southern Observatory

On top of Cerro Armazones, deep in the Atacama Desert in northern Chile, a new feature is set to dominate the landscape over the next decade. Sitting 20 kilometres (12.4 miles) from the Paranal Observatory, the European Extremely Large Telescope (E-ELT) will, when complete, become the world's largest eye on the sky.

It will enable 15 times more detail than the Hubble Space Telescope and take astronomy to places it has never been before, letting scientists gain insights into the nature of black holes, dark matter, as well as energy and galaxy formation. It will push human knowledge of space forward to unprecedented heights.

Dr Joe Liske, a German astronomer based at the European Southern Observatory, believes this is driving the 14 member states, from Austria to Germany, Sweden to Switzerland and the UK, to throw their weight behind the €1.1 billion (£881 million / $1.5 billion) project. Such is the scale of the project that the first non-European nation, Brazil, is about to become the 15th member.

"Everything about the E-ELT is huge," says Dr Liske. "The mountain is 3,064 metres [10,052 feet] high but we're going to take 18 metres [59 feet] off the top of it to create a platform big enough the hold the telescope. The platform on top of the mountain will be more than 150 metres [492 feet] in diameter, housing a telescope building of 90 metres [295 feet]. Inside the building will be a telescope with a 39.1-metre- [128-foot-] diameter segmented primary mirror. It's going to be quite a sight."

However, it could have been even bigger. "We were studying the possibility of building a 100-metre [328-foot] telescope, which had the great acronym OWL – Overwhelmingly Large Telescope," he laughs. "But it was too expensive and technically too risky. They decided to be modest and go for 42 metres [138 feet] before scaling it slightly back to the current level."

Underpinning the need for a large telescope is the ESO's desire to see Earth-like planets around other stars. Scientists want to study them in enough detail so that they can look for signs that there may be life on one of these planets. Dr Liske says only a telescope of approximately 40 metres (131 feet) will enable astronomers to achieve this to its full potential. "If you go far below this size, then you lose that ability," he explains.

In order to achieve the size scientists need, the telescope itself will be made up of a large set of mirrors rather than a single piece of glass. "You just can't make a single piece of glass 39 metres [128 feet] in diameter," Dr Liske says. The primary mirror is broken into 798 smaller hexagonal segments around 1.42 metres (4.66 feet) across. It's not a pioneering method: the Keck telescopes on Mauna Kea in Hawaii and the Gran Telescopio Canarias, run by Spain on La Palma, are also segmented. "But what we've done with the E-ELT is take this concept of segmenting a primary mirror to a whole new level," continues Dr Liske. "The Keck has 36 segments so ours will be on an entirely different [scale] in terms of controlling the telescope. Each of the segments will be individually mounted and steerable. We'll be able to move them up and down, tilt them around two axes and even change their shape, and this will benefit us because we'll be able to get the best possible image quality out of our telescope."

The huge primary mirror affects the sharpness of the image collected by the telescope. This is fundamental physics, Dr Liske explains, or more specifically optics law. Light is reflected from the primary mirror to four smaller mirrors which in turn direct it to cameras and other interchangeable measuring instruments.

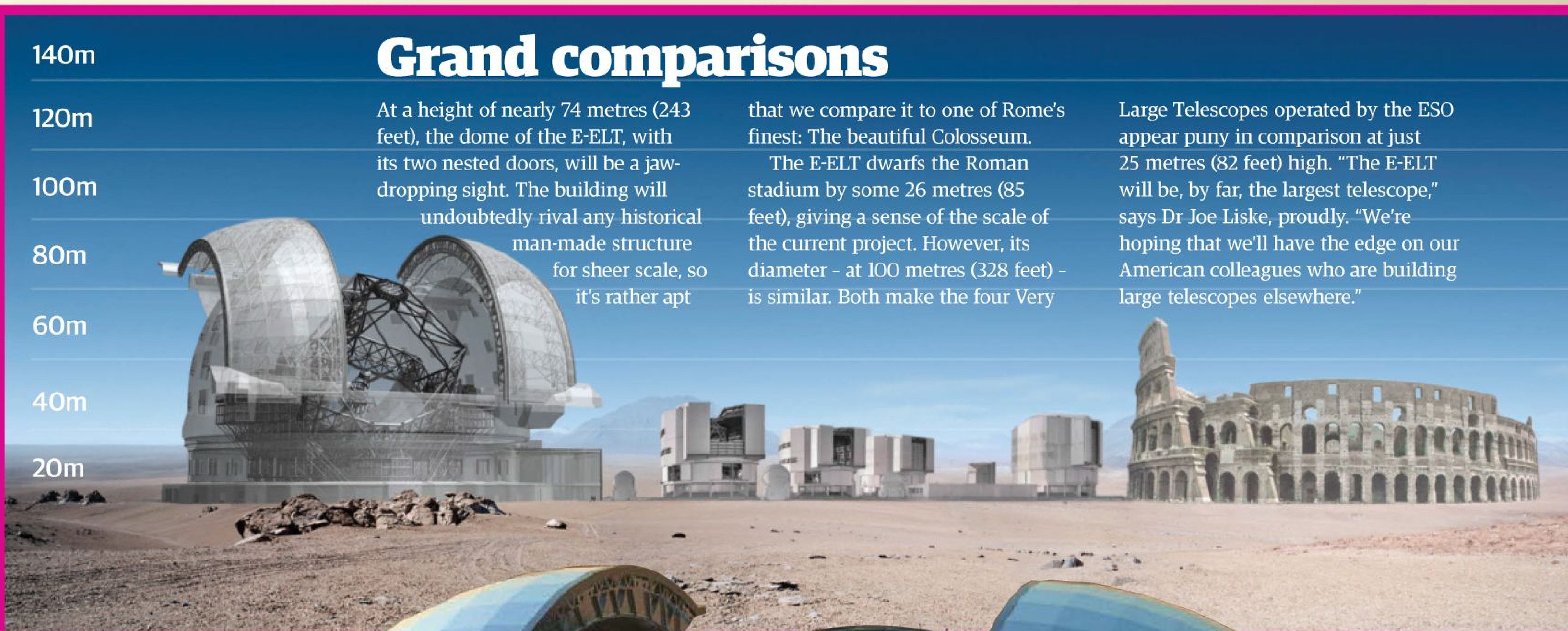
But what makes the E-ELT's large size even more impressive is that it can collect more light than all of the existing eight- or ten-metre- (26- or 33-foot-) class telescopes on the planet put together. "We'll be able to see the same objects as we could see before, only to much greater distances, or at a fixed distance we could see intrinsically fainter objects," Dr Liske explains. "Both of those things are important to astronomers because we want to see further out into the universe." The E-ELT is earmarked for completion in 2024. "It's an exciting time to be involved," Dr Liske says. You cannot fail to agree.

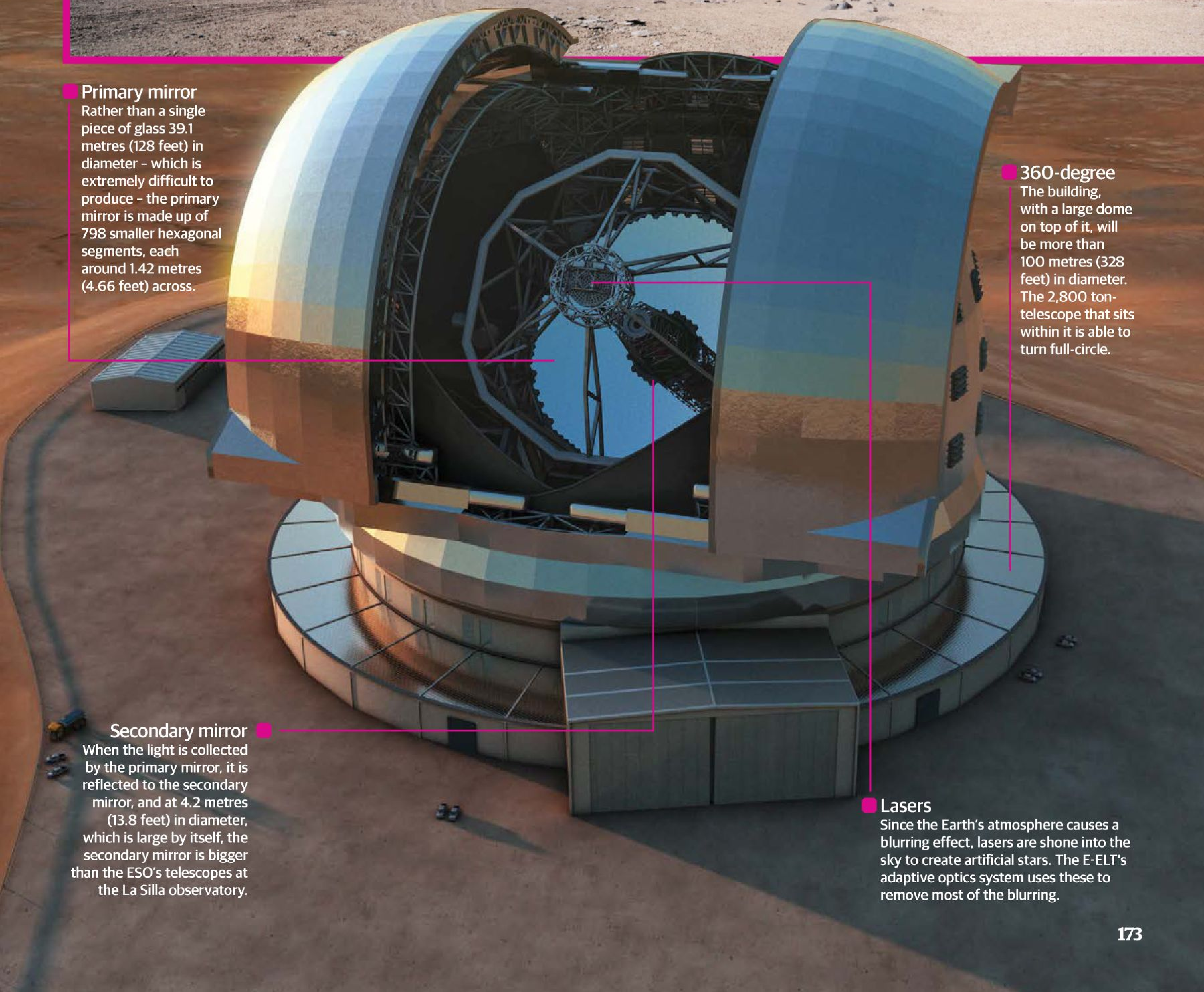
More mirrors
The tubular device in the centre of the telescope contains three more mirrors. One at the bottom relays light to an adaptive mirror above it. Distortions are corrected. A middle mirror stabilises the image.

Grand comparisons

At a height of nearly 74 metres (243 feet), the dome of the E-ELT, with its two nested doors, will be a jaw-dropping sight. The building will undoubtedly rival any historical man-made structure for sheer scale, so it's rather apt that we compare it to one of Rome's finest: The beautiful Colosseum.

The E-ELT dwarfs the Roman stadium by some 26 metres (85 feet), giving a sense of the scale of the current project. However, its diameter – at 100 metres (328 feet) – is similar. Both make the four Very Large Telescopes operated by the ESO appear puny in comparison at just 25 metres (82 feet) high. "The E-ELT will be, by far, the largest telescope," says Dr Joe Liske, proudly. "We're hoping that we'll have the edge on our American colleagues who are building large telescopes elsewhere."





Primary mirror
Rather than a single piece of glass 39.1 metres (128 feet) in diameter – which is extremely difficult to produce – the primary mirror is made up of 798 smaller hexagonal segments, each around 1.42 metres (4.66 feet) across.

360-degree
The building, with a large dome on top of it, will be more than 100 metres (328 feet) in diameter. The 2,800 ton-telescope that sits within it is able to turn full-circle.

Secondary mirror
When the light is collected by the primary mirror, it is reflected to the secondary mirror, and at 4.2 metres (13.8 feet) in diameter, which is large by itself, the secondary mirror is bigger than the ESO's telescopes at the La Silla observatory.

Lasers
Since the Earth's atmosphere causes a blurring effect, lasers are shone into the sky to create artificial stars. The E-ELT's adaptive optics system uses these to remove most of the blurring.

GMT: It's time for the next generation

Featuring the world's most advanced mirrors, impressive defence against the elements and some of best images imaginable

INTERVIEW BIO

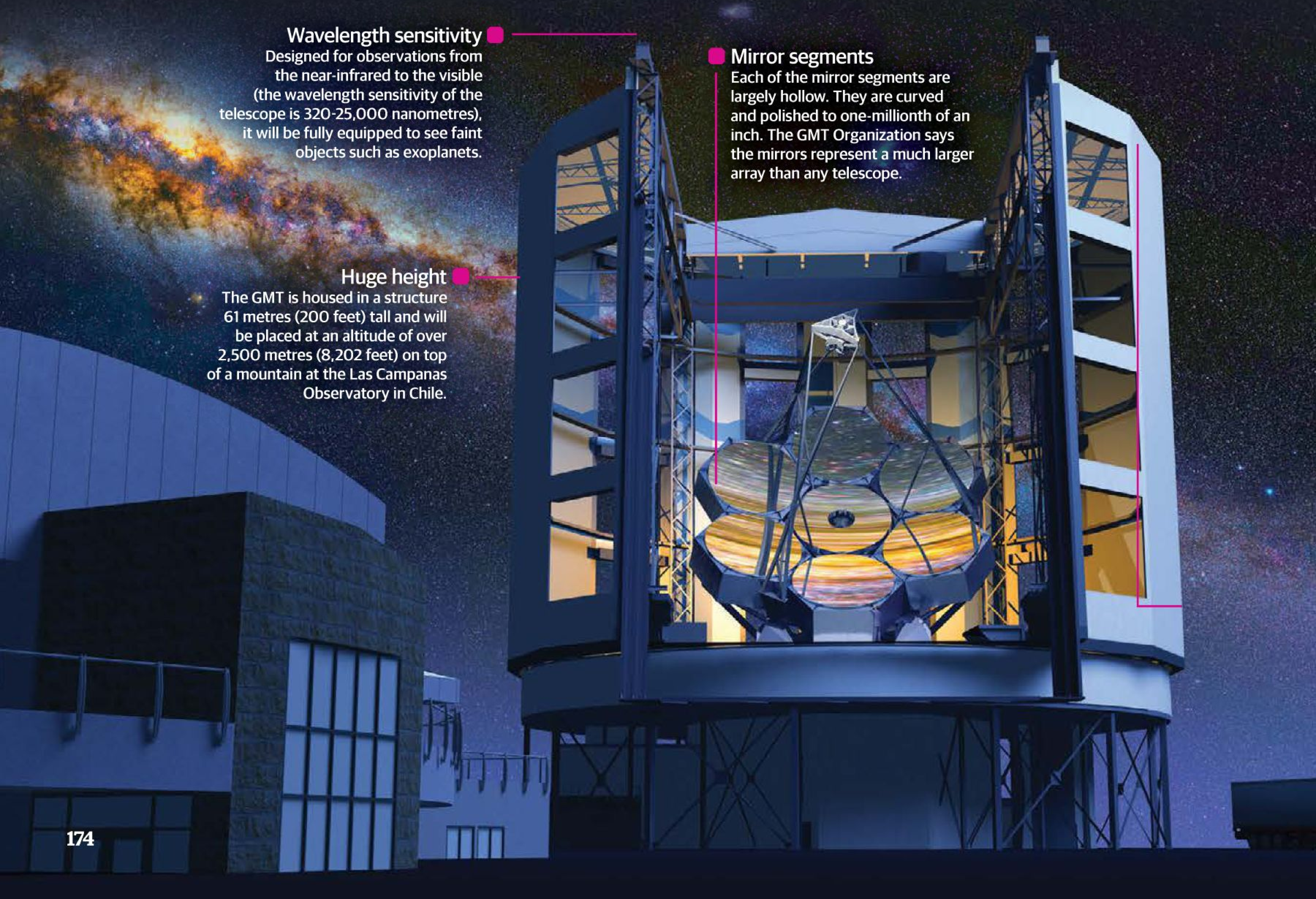
Patrick McCarthy
Director
GMT Organization

The Giant Magellan Telescope will be smaller than the E-ELT but it's by no means inferior. Scientists at the University of Arizona and in California claim it will contain the world's most advanced mirror. What's more, the GMT will contain seven of them.

Work has already started on the telescope. Astronomers have blasted 85,000 cubic metres (3 million cubic feet) of rock from the top of a mountain in the Chilean Andes and this will provide a base for the structure at the Carnegie Institution's Las Campanas Observatory, which is now poised to enter the construction phase.

The idea for the telescope goes back to 2000, when astronomers noted that the large structured mirrors made in Arizona were producing outstandingly good images. "They were producing images that were actually better than we expected," says Dr Patrick McCarthy, director of the GMT Organization. "They performed well mechanically, they're very stiff and they're polished to exquisite precision in Arizona. We learned how to control them on the mountain tops, manage their temperature and adjust their shapes. People then started thinking about the next stage: how we could go from a ten-metre [33-foot] telescope to 20 or 30 metres [66 or 98 feet]."

While the primary mirrors of the E-ELT and TMT will be made up of small segments, the GMT takes six 8.4-metre (27.6-foot) mirrors and arranges them off-axis in a lotus petal shape around a central



Total collecting area
The seven 8.4-metre- (27.6-foot-) diameter mirrors combine to produce one large mirror with a total collecting area of 368 square metres (3,961 square feet).

"It will enable them to collect fantastic images at the most cost-effective price"

mirror, making seven in total. This forms a single optical surface with an aperture of 24.5 metres (80 feet) and because the mirrors are stiff, as Dr McCarthy points out, they will be able to cope well with the windy elements high up.

The telescope will also benefit from adaptive optics. Flexible secondary mirrors adjust to counteract atmospheric turbulence so, as with the other two telescopes, which also use such a system, the GMT will be able to correct atmospheric blurring. Since it has a large aperture that can hold images three times sharper than the limit for eight-metre (26-foot) apertures around today, the GMT will have resolution unlike that of any current system.

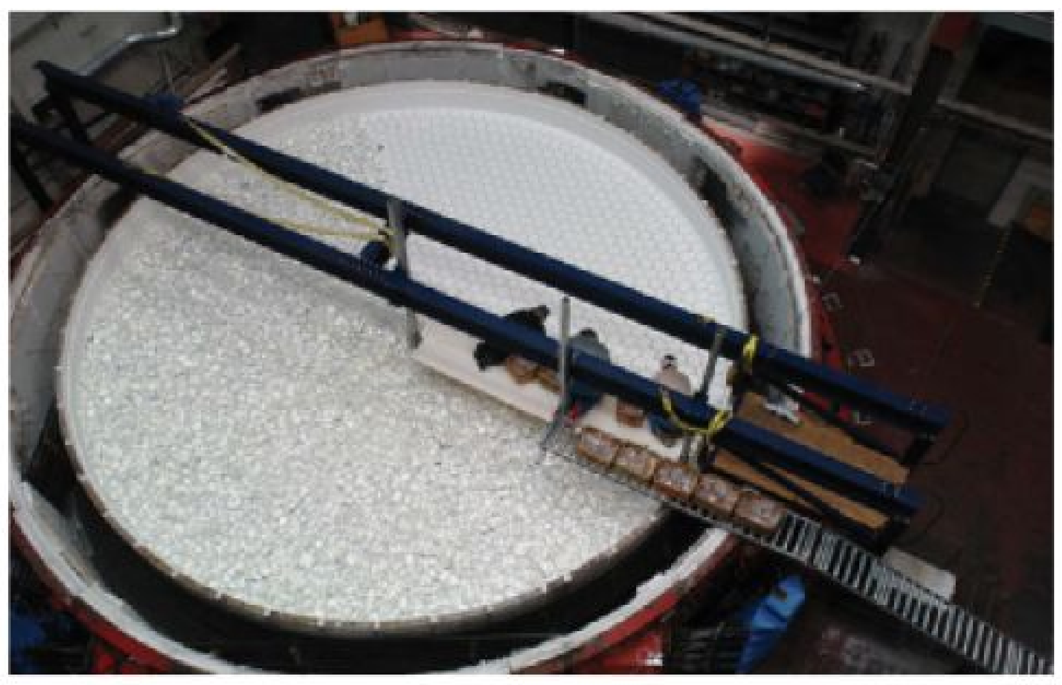
"It became clear that the new emerging field of exoplanets – the study of planets around other stars – really was crying out for a larger aperture," he says. "It really requires the improved performance from a large telescope in terms of diffraction-limited imaging, in terms of thermal background and just overall sensitivity."

By using these structured mirrors, the team can make a telescope that will be compact and optically fast. It's smaller than the E-ELT – the telescope could have had more than seven mirrors but that was the maximum the team aimed at, primarily to keep down costs – but Dr McCarthy says the difference between the two telescopes in terms of scientific performance will be slight. "I think scientists will see the same thing with the different 30-metre- [98-foot-] class telescopes," he says.

The GMT will provide them with ten times as much detail as the Hubble Space Telescope and by basing it in Chile at an altitude of over 2,500 metres (8,202 feet), it will enable them to collect fantastic images at the most cost-effective price ($1.05 billion or £610 million). The centre of the galaxy and all the major star-forming complexes go right overhead of Chile, which means the telescope can look almost anywhere in the sky outside of the Milky Way and get a fair sample of young planets.

"If you want to find locations on Earth that are well-suited to optical and infrared astronomy, you want to find a place that's dry and has clear weather," says Dr McCarthy. "But it's critical to have locations in which the air flow is very smooth, where the air is flown for hundreds and thousands of miles unimpeded before it reaches your mountain top. The Chilean Andes is perfect and there's no prospect of light pollution because it's so remote."

The GMT will enable astronomers to discover more about the universe than ever before. "We have a large list of other interesting topics involving looking back at the early universe to see the first galaxies, measuring the growth of black holes and so on and so on," Dr McCarthy says. It is set to go live in 2020.

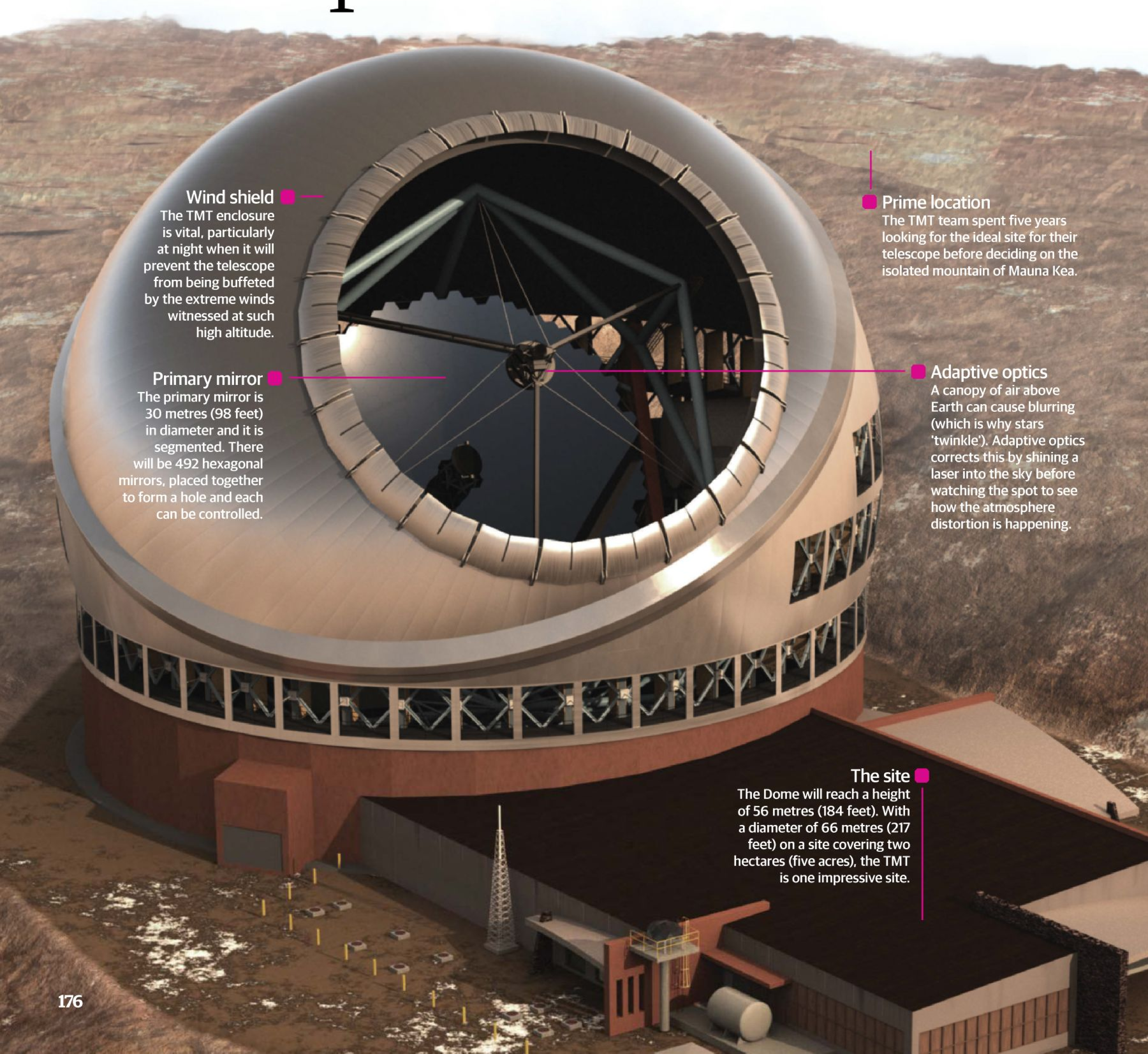


Made of glass

Constructed by the University of Arizona's Steward Observatory Mirror Lab, each of the seven mirror segments that will make up the GMT will be cast from 20 tons of glass. Our picture shows the glass being loaded into the 8.4-metre (27.6-foot) diameter furnace mould one piece at a time. When this job is complete, the lid will be placed on top and it will be heated to 1,170 degrees Celsius (2,138 degrees Fahrenheit) to melt the glass into the mould. The mirror is then polished to match a precision of 19 nanometres using a series of fine abrasives. It will then be assembled with the other mirrors to form a single 25-metre (82-foot) optical surface. So far three segments have been cast and the fourth will be ready for casting in 2015. Even though there will be seven mirrors in total, astronomers will be able to start their observations with just four in place.

China in their hands: The truly international telescope

Find out how the Thirty Meter Telescope plans to be the world's best



INTERVIEWBIO

Dr Luc Simard
Group Leader – Instrumentation
National Research Council of Canada's Herzberg Institute of Astrophysics

Larger than the GMT but smaller than the E-ELT, the Thirty Meter Telescope (TMT) represents the middle ground. As the name suggests, this telescope will have a mirror 30 metres (98 feet) in diameter at its heart and it will have a collecting area of 655 square metres (7,050 square feet). The astronomers working on it say it will become the most advanced and powerful optical telescope on Earth.

Unlike its rivals, the TMT is set to be built, not in Chile, but at the Mauna Kea Observatory in Hawaii and it is the culmination of three major projects: the California Extremely Large Telescope, the Very Large Optical Telescope in Canada and the Giant Segmented Mirror Telescope, each of which have merged into one scheme.

It is a truly international affair with the University of California, the Californian Institute of Technology, Canada, China, India and Japan joining forces. By combining such expertise, the project has been able to draw upon some very experienced astronomers.

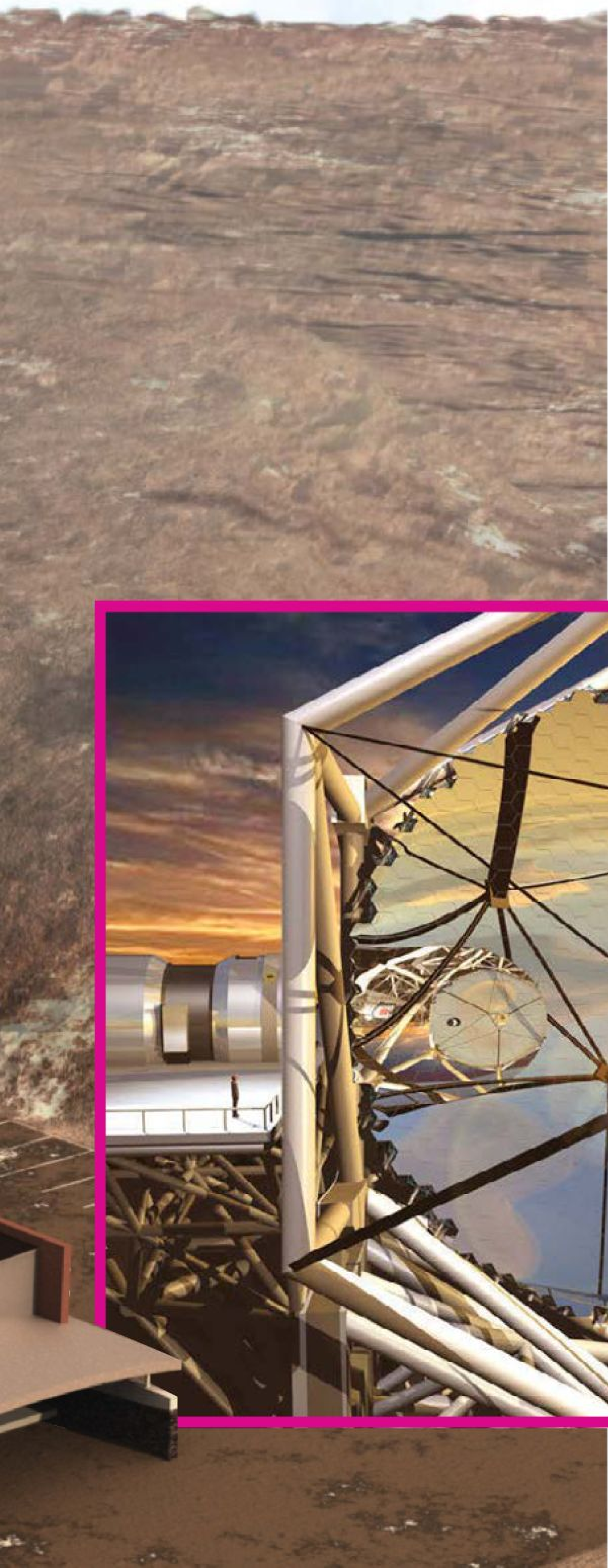
One of those is Dr Luc Simard who is developing instruments for the TMT. "The TMT continues the technology of Keck which has a ten-metre [33-foot] mirror made up of 36 segments of 1.8 metres [5.9 feet]," he says. "We are using 492 segments, each one 1.4 metres [4.6 feet] in diameter. Since we are using slightly smaller segments and many more of them, we will be able to better control the alignment and phasing when the telescope is being moved around the sky." The 492 segments behave as a single monolithic mirror that is 30 metres [98 feet] in diameter. "It's quite a powerful technology; it's very beautiful, it really scales nicely," Dr Simard says.

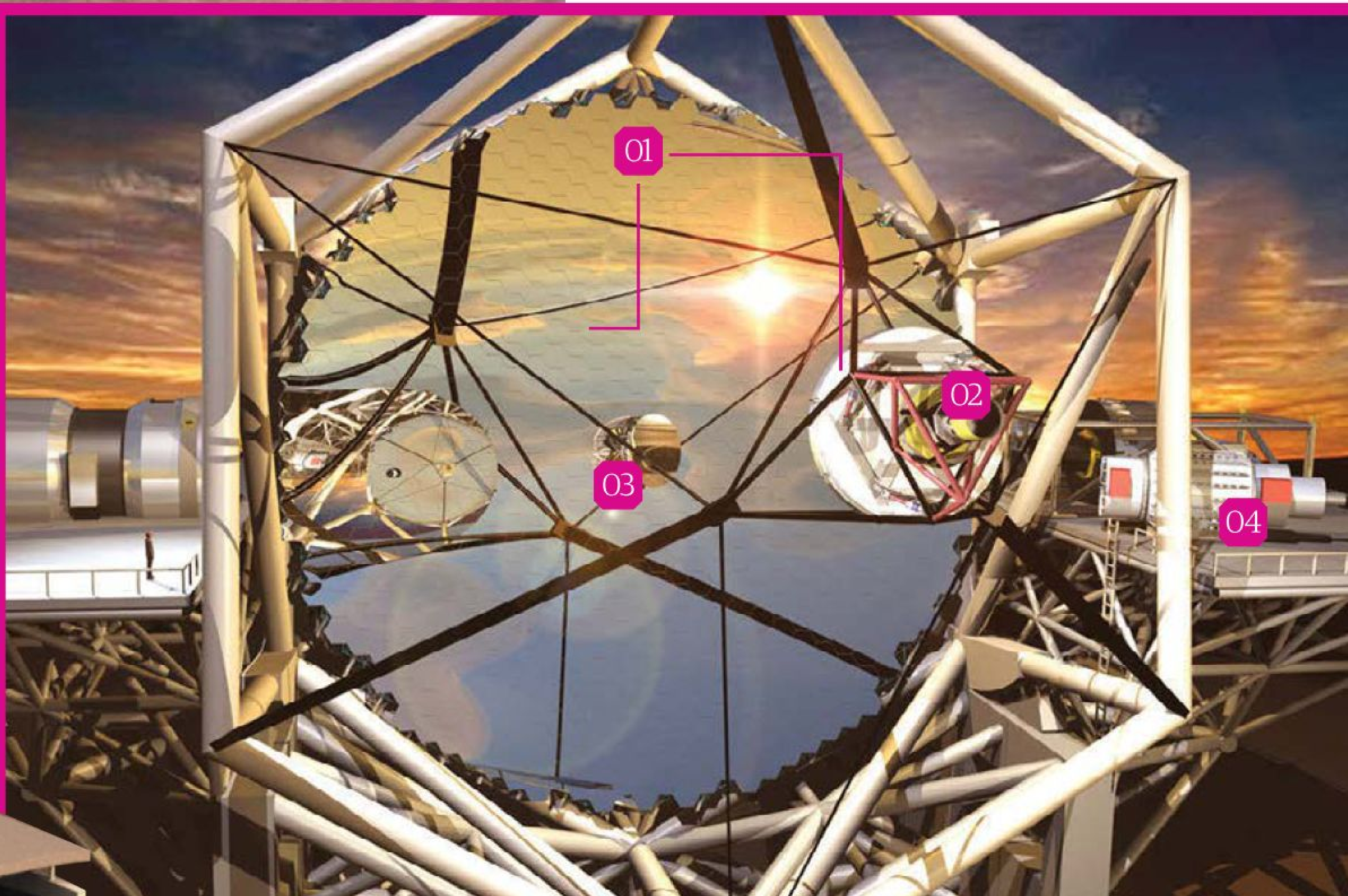
A secondary mirror will be three metres (9.8 feet) in diameter, which is as large as the primary mirrors of some telescopes currently in use. Working in tandem, the telescope will have nine times the collecting area of the largest telescopes around today. "That's the cool thing when you build a bigger telescope – you end up with a finer angle of resolution," he says. "So let's say you took the diameter of the full moon and you divided the diameter by two million parts, you'd be able to see about seven of those parts with TMT and that's how powerful it is." He would have loved to see the TMT even bigger than it is and says, if money was no object, that would be possible. But he adds: "There is no doubt that what we have is powerful and when you use it to look into the sky, it will show everything moving. It's the kind of thing a fine machine like TMT will be able to achieve."

By building adaptive optic systems on large platforms surrounding the telescope, astronomers will be able to shrink the size of the images so that they are close to the diffraction limit of the telescope. The diffraction-limited spatial resolution will exceed Keck by a factor of three. "Our telescope is going to be almost 200 times more powerful than the current class of eight- to ten-metre [26- to 33-foot] telescopes," he adds.

TMT is being built to be a fine all-rounder, equally at home when aimed at the Solar System to study the Moon and its planets to discover more about them as it will be looking at its outer edge. By basing it at Mauna Kea, the team believes it will have a prime spot for the telescope, allowing astronomers to observe near-ultraviolet to mid-infrared wavelengths.

The TMT will find itself 4,050 metres (13,287 feet) high – higher in altitude than the mountains being used by its rivals in Chile. "It is a really truly excellent site in terms of the number of clear nights, dryness and altitude," Dr Simard says. "You're above most of the cloud cover and above most of the water vapour in the atmosphere. It's a premier site."





TMT in focus

1 Spacing
The spacing between the segments of the primary mirror is less than three millimetres (0.1 inches). The primary and secondary mirrors are hyperboloidal and together they create a well-corrected focus.

2 Laser beams
The Laser Launch Telescope will project a constellation of six laser beams into the upper atmosphere and this will create artificial reference stars.

3 Optical axis
The optical axis of the telescope (that is, the location of the tertiary mirror) is 23 metres (75 feet) above the floor of the observatory dome, which is highly impressive indeed.

4 Grand scale
The TMT science instruments (which you can see in this picture as the cylinders on the two side platforms) are in-keeping with the overall structure: they are the size of small buildings.

What will they see?

The telescopes will boldly go where no man has gone before without even leaving Earth. But what do astronomers hope to achieve?

Astronomers believe the new wave of large telescopes will allow them to make breakthroughs that current technology simply does not allow. But the fondest hope of scientists is that they discover something completely unexpected. "And that's the most exciting thing," says Dr Patrick McCarthy.

Still, astronomers have a long list of items they would like to address and which they predict the large telescope will enable them to achieve. First on many an astronomer's list is the ability to show conclusively that there are planets out there that are conducive to supporting life.

While scientists know there are Earth-like planets that are perhaps a little larger or smaller than our own planets, if the telescopes are any indication of a new space race, then being among the first to find them will be a prime motivation. So far, none of the 1,500 exoplanets that we know of are similar enough to Earth, but it is envisaged that hundreds more will be spotted with these new telescopes, some of which may be better matched.

It is, therefore, hoped that the large telescopes will enable scientists to find water-carrying planets that are in the right temperature range. They want to find biomarkers of oxygen, methane and other chemical and molecular species that are believed to be directly related to biological processes. The telescopes will give them a very good chance of discovering life on the surface of an exoplanet, indicating whether they are covered by a rocky surface or an ocean or whether or not they contain vegetation.

The telescopes will also enable scientists to look back even further in time, uncovering the very first generation of galaxies in the universe. "We want to observe the first stars because they are very different from our own Sun," says Dr Luc Simard. "They start the story of nuclear synthesis – you can trace the products of the nuclear synthesis inside stars all the way to our own bodies."

With the ability to see the centre of the Milky Way and study a black hole 4 million times the mass of the Sun, and with hopes of being able to directly measure the acceleration of the universe's expansion, there is the possibility of our comprehension of the general laws of physics being redefined in some way.

It helps enormously that the new telescopes are able to take images at very high resolution. In doing so, scientists will be able to visually separate a planet orbiting a star from the bright glare of its parent. "Think of yourself getting onto a spaceship, flying far away from the Earth and then turning round," says Dr Joe Liske. "You'd see something extremely bright – the Sun – and something very faint – the Earth. But from a distance of a few light years, the Sun and Earth appear extremely close together. The large telescopes would change that kind of view – we'd be able to get a greater sense of their position."

With new scientific frontiers opened up, astronomers will not only uncover objects they did not know existed but also discover things they thought they knew were wrong. The discoveries won't happen straight away – it may take a few years for the scientists to learn how to make the telescope and instruments work effectively – but there should be some early advancements. We should start seeing science from 2021 and it is set to be exciting.

> "There is the possibility of our comprehension of the general laws of physics being redefined"

Gamma-ray bursts
So far, existing telescopes have been useful in telling scientists more about the burst of energetic gamma-rays. The visible light following a short-duration burst was seen for the first time in 2005. The E-ELT will see with greater clarity.

Exoplanets
There are hopes of finding an Earth-like planet reasonably close to Earth – within 30 light years or so – over the next 12 months. Once found, it will form a major target for scientists working with the E-ELT to probe them further.

Early galaxies
Astronomers want the E-ELT to work together with the James Webb Space Telescope to try and uncover the first generation of galaxies in the universe. They want to go back much further than ever before.

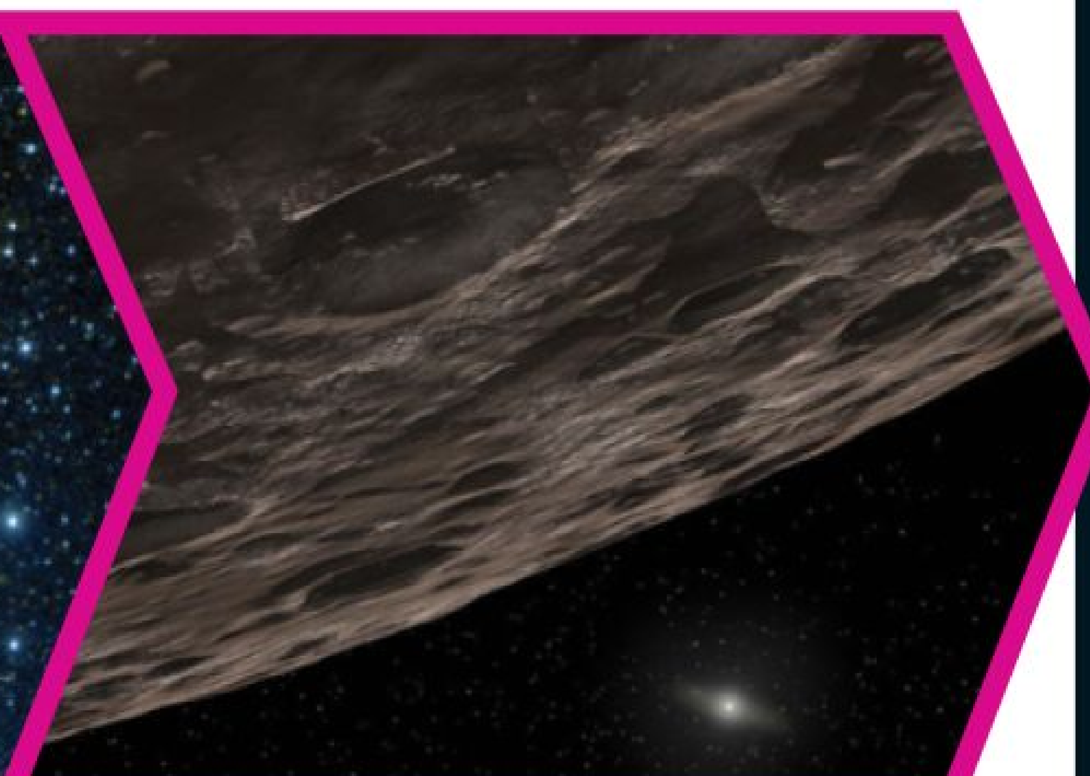
Planetary systems
With around 100 planetary systems well understood in terms of their orbital structures and dynamics, the team at GMTO believe between 30 and 40 of them will be clearly viewable from Chile, enabling teams to study them further.

Cold Jupiters
Hot Jupiters are the easiest extrasolar planets to uncover, which tells you that cold Jupiters are not. But because the GMT can gather light from deep into space, scientists could see Jupiter-like planets further away from their star.

Black holes
The GMTO team will be looking specifically at black holes to a distance of half way back to the Big Bang. They want to measure masses, see how they grow, ingest gas and see if they merge with other black holes.

The Moon
Sure, mankind has actually set foot on the moon. We know it's not made of cheese. But the TMT will be able to get up close and monitor its surface in real time to study any possible changes that are occurring.

Star clusters
According to Dr Luc Simard, one of the races among the three teams involved in the three telescopes could see them battling to get the first high-resolution shot of the galactic centre of a star cluster.



Kuiper belt
Beyond the planets and extending from Neptune's orbit to the sun, this huge band of objects from the formation of the Solar Systems is begging for exploration. TMT's team want to look at the chemistry.

5 things they could discover

01 More about General Relativity
Scientists will look at the orbiting stars around the supermassive black hole sitting in the centre of the Milky Way. Studying their behaviour will help them test general relativity in the vicinity of a black hole.

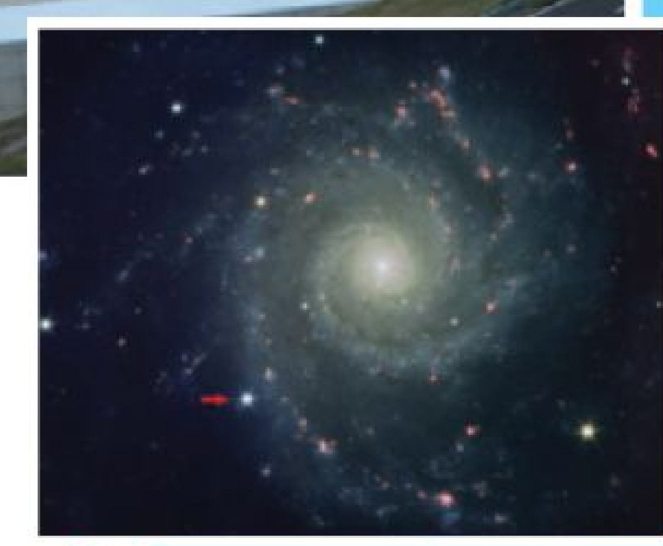
02 New regions
A hundred years ago, no one expected the universe to be as large as we know it is today nor did they realise it was expanding. Telescopes opened up new regions of space and the next generation will be looking to do the same.

03 Enhanced astrometry
As soon as the telescope gets going, it will provide a very powerful adaptive optic system and that means the field of astrometry – taking precise measurements of the positions of celestial bodies – will be revolutionised.

04 Dark matter's composition
By being able to gather more light, the high-resolution telescopes will be able to study the dark matter and dark energy that comprises much of our universe.

05 Evidence of life
Are we alone? It's the big question and by studying the earliest stages of the formation of planetary systems, scientists hope detecting water or organic molecules will answer it once and for all, opening up whole new waves of intrigue and research.

10 of the world's biggest telescopes



The GTC is the largest optical telescope in the world

Large Zenith Telescope

Location: Maple Ridge, British Columbia, Canada
Diameter: 6m/20ft
Able only to look at the zenith – an imaginary point directly above the spot being studied – the LZT can measure spectral energy, distributions and redshifts of more than 100,000 galaxies and quasars.

Large Binocular Telescope

Location: Mount Graham International Observatory, Arizona, USA
Diameter: 8.4m/27.6ft
Using two 8.4-metre- (27.6-foot-) diameter mirrors, this telescope can gather the same amount of light as one 11.8 metres (38.7 feet) in diameter.

Hobby-Eberly Telescope

Location: McDonald Observatory, Texas, USA
Diameter: 9.2m/30.2ft
This huge telescope was built with a budget in mind, but it does not compromise on quality. It is to be expanded with 150 integral field spectrographs, enabling it to map the expansion rate of the early universe.

Keck

Location: Mauna Kea Observatories, Hawaii
Diameter: 10m/32.8ft
There are two, identical segmented mirror Keck telescopes in Mauna Kea, built in the mid-1990s and later equipped with laser guide star adaptive optics. As well as taking stunning images of planets, in 2009, it detected methane on Mars, an indicator of possible life.

VLT

Location: Paranal Observatory, Chile
Diameter: 8.2m/26.9ft
Four Unit Telescopes with 8.2-metre- (26.9-foot-) diameter mirrors combine with four movable 1.8-metre- (5.9-foot-) diameter Auxiliary Telescopes to create the world's most advanced optical instrument, letting astronomers see impeccable detail

The twin Keck telescopes detected methane on Mars

Gran Telescopio Canarias

Location: Roque de los Muchachos Observatory, Canary Islands, Spain
Diameter: 10.4m/34.1ft
Currently the largest optical telescope in the world, the GTC made its first observation in 2007. Sitting atop a volcanic peak at an altitude of 2,267m (7,438ft), it has picked up galaxies as far as 25 million light years away.

Magellan

Location: Las Campanas Observatory, Chile
Diameter: 6.5m/21.3ft
These two telescopes are located 60 metres (197 feet) apart. The mirrors are made of borosilicate glass with a lightweight honeycomb structure. They are said to be the best natural imaging telescopes in the world.

BTA-6 has found new binary and multiple-star systems

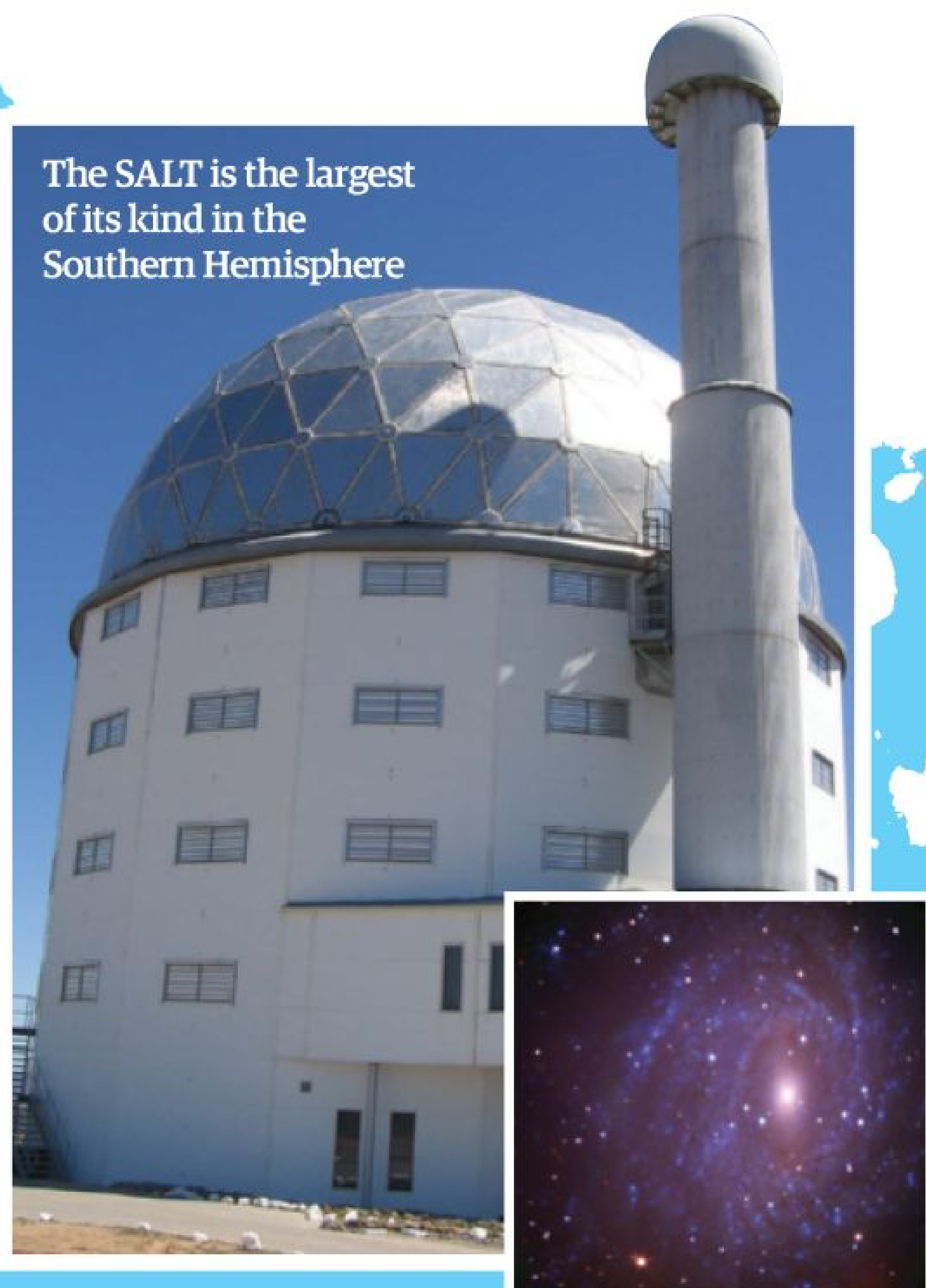
A quadruple star system imaged in visible light by BTA-6

BTA-6

Location: Special Astrophysical Observatory, Russia
Diameter: 6m/19.7ft
The BTA-6, in the Caucasus Mountains of Russia, was dubbed a white elephant soon after it began to operate due to issues with the mirror. Since rectified, it recently discovered new binary and multiple star systems with magnetic compounds.

Anglo-Australian Telescope

Location: Siding Spring Observatory, New South Wales, Australia
Diameter: 3.89m/12.8ft
Celebrating 40 years on Earth, many scientific publications have been based on the discoveries of this telescope. In 2013, scientists in Australia found the last giant outburst of energy from the supermassive black hole in the centre of our galaxy took place two million years ago.



The SALT is the largest of its kind in the Southern Hemisphere

The Anglo-Australian Telescope is over 40 years old

Southern African Large Telescope

Location: South African Astronomical Observatory, Northern Cape, South Africa
Diameter: 9.8m/32.2ft
As the largest ground-based optical instrument in the southern hemisphere, its hexagonal primary mirror is over 9.8 metres (32.2 feet) in diameter. It's aim is to study the absorption and emission of light and other radiation by matter of astronomical objects.

Dyson sphere

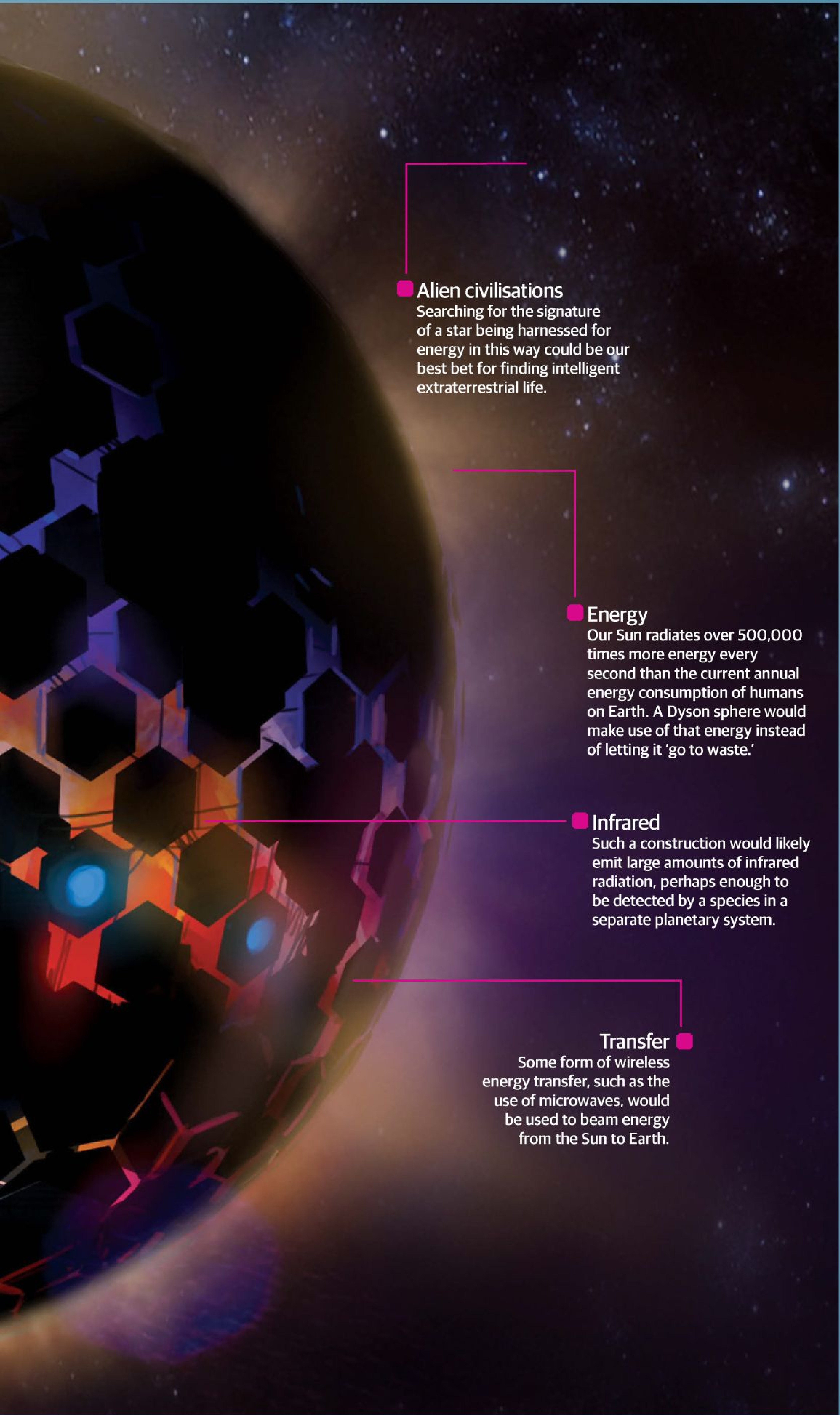
Could an advanced civilisation harness the power of stars to sustain their energy needs?

Satellites
The diameter of the Sun is 100 times greater than Earth, so we'd need to evenly spread out solar power satellites to gather energy for transfer to Earth.

Mass
If the satellites were fairly small, the amount of material needed to build them would reduce drastically, therefore making the proposal more feasible.

Sails
The satellites would be kept in position around the star by virtue of large light sails, which would use the radiation pressure of the star to counteract the force of gravity.

Poles
A 'swarm' of orbiting satellites is preferred to a solid sphere, as the latter would likely lose structural integrity at the poles where there was no rotation.



First proposed by physicist Freeman Dyson in 1960, a Dyson sphere is a hypothetical swarm of satellites that would surround a star in order to harness its energy. Although more commonly known as a Dyson swarm, some people have discussed the possibility that, rather than a swarm of satellites, a star could be encased in a solid sphere by a future civilisation. But this is an idea that Dyson himself is keen to stray away from. Indeed, for a planetary system like our own, such a structure would likely require every object in the Solar System other than the Sun to be dismantled and rebuilt into a giant sphere owing to the huge size of the Sun.

Dyson's initial proposal was suggested as a way that a future civilisation could sate their vast energy needs. As the energy requirements of a civilisation increases they may require an ever-growing amount of energy, a crisis perhaps solved only by harnessing the power of stars. With it this carries further connotations, that there may be advanced races elsewhere in the Solar System that have built such structures. Dyson postulated that these would radiate a large amount of infrared radiation noticeable even to us here on Earth.

The idea has gained enough ground that the SETI Institute in California, USA, has been on the lookout for Dyson spheres, while Fermilab near Chicago has carried out its own analysis of observations from outside the Solar System to ascertain the likelihood of the existence of Dyson spheres. Aside from finding four candidates that were "amusing but still ambiguous and questionable," though, nothing too promising has been found.

While fun to imagine, the logistics of a Dyson sphere are also quite far-fetched. Taking the solid shell idea, this structure would be thin at perhaps just a few tens or hundreds of metres thick with its membrane covered in solar panels, but it would still be many times more massive than Earth. Placed around a star, though, it would have little chance of keeping its structural integrity; if made to rotate so as to keep it in 'orbit' around the star, the areas around its artificial equator would be stable but at the poles, where there was no rotation, the structure would succumb to the forces of gravity and collapse.

This is why Dyson favours the swarm idea. With this, many thousands of solar energy-gathering satellites would be placed around the star. They would then beam their energy to a central hub to be utilised by a civilisation. Using separate satellites, all in orbit around the star, the structure would remain intact and huge amounts of energy could be transferred from the star.

While this particular structure might seem impractical, something on a smaller scale could feasibly do a similar job. For example, some theories suggest that a large solar-gathering spacecraft placed between Earth and the Moon would be able to absorb huge amounts of power that could be beamed to our planet. Known as space-based solar power (SBSP), this is something that sci-fi writers have favoured and is a much more promising technology than an entire Dyson sphere. However, perhaps many thousands of years in the future when we become interstellar explorers, it may be necessary to find huge resources of energy and, as far as we know, there's nothing better than an entire star.

10 INTREPID FUTURE LANDERS

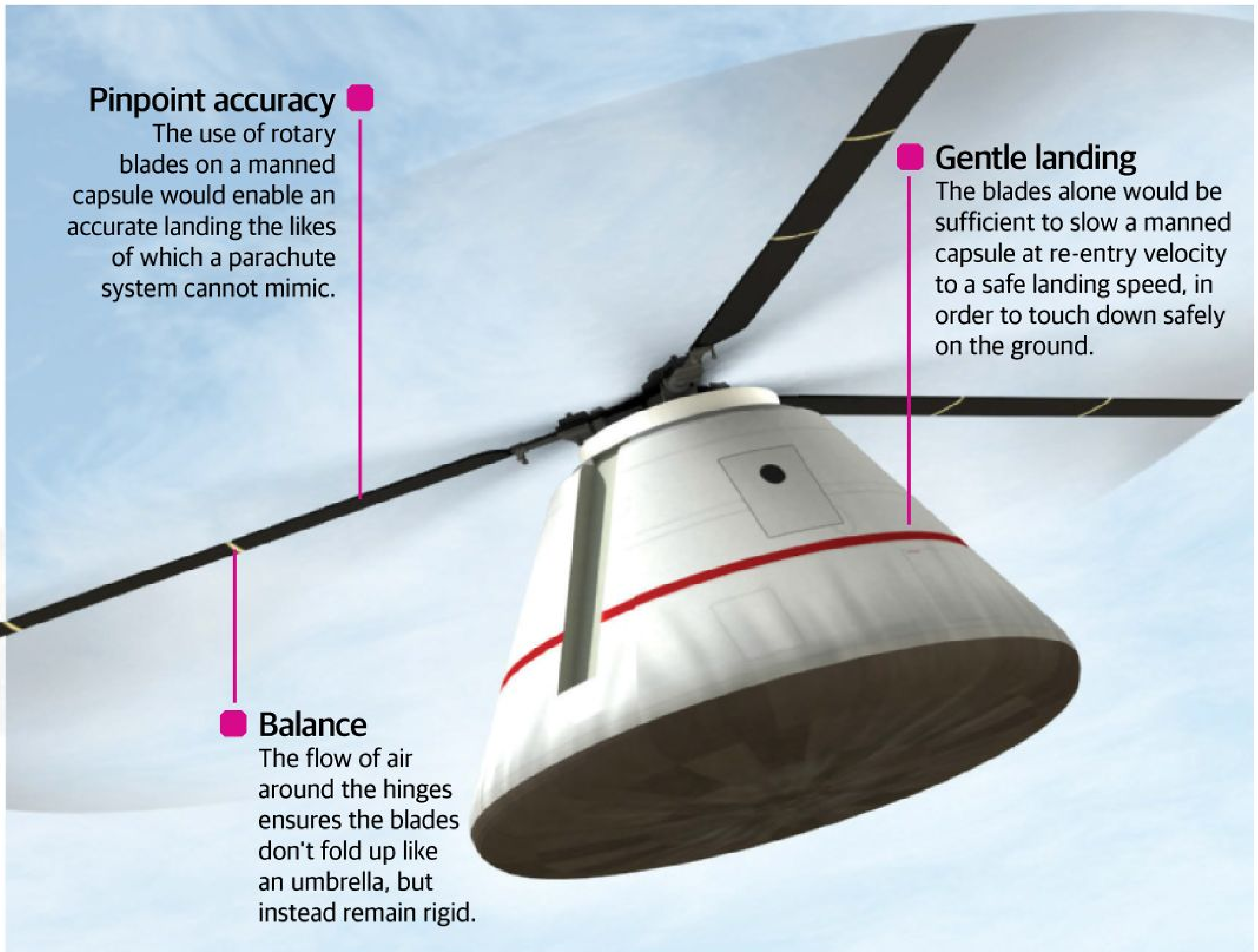
Innovative machines that could enable us to explore the cosmos like never before

Landing spacecraft on other worlds in the Solar System, or even our planet, is not an easy business. On Earth you have to contend with a thick atmosphere coupled with a relatively strong gravitational pull when compared with elsewhere. When tackling distant worlds there's also the small matter of getting there in the first place before attempting to traverse unchartered terrain.

While we have tried and tested many methods to land spacecraft, from parachutes on Earth to the Sky Crane employed by NASA to land Curiosity on Mars, many of these methods limit what sort of spacecraft or vehicle we can land.

When it comes to places like Europa, we just don't have a means of reaching its subsurface ocean. Researchers and scientists have been busy designing new contraptions that could bring about multiple revolutions in landing technology, so here we've taken a look at ten of the most exciting innovations that could be heading our way in the near future.


SPACEX
DRAGON



1 Roto Capsule

Landing capsules with parachutes could be a thing of the past if this promising technology comes to fruition. Researchers at NASA have been looking into the possibility of using rotary blades, akin to those found on a helicopter to safely return a manned capsule to a precision landing on Earth, instead of the rather less-precise landings offered by parachutes.

These rotors are slightly different from helicopter blades, however. They aren't powered, but instead use the passing wind to turn in a process known as auto-rotation. This method has been tried and tested on helicopters, but it has never been applied to a vehicle returning from space.

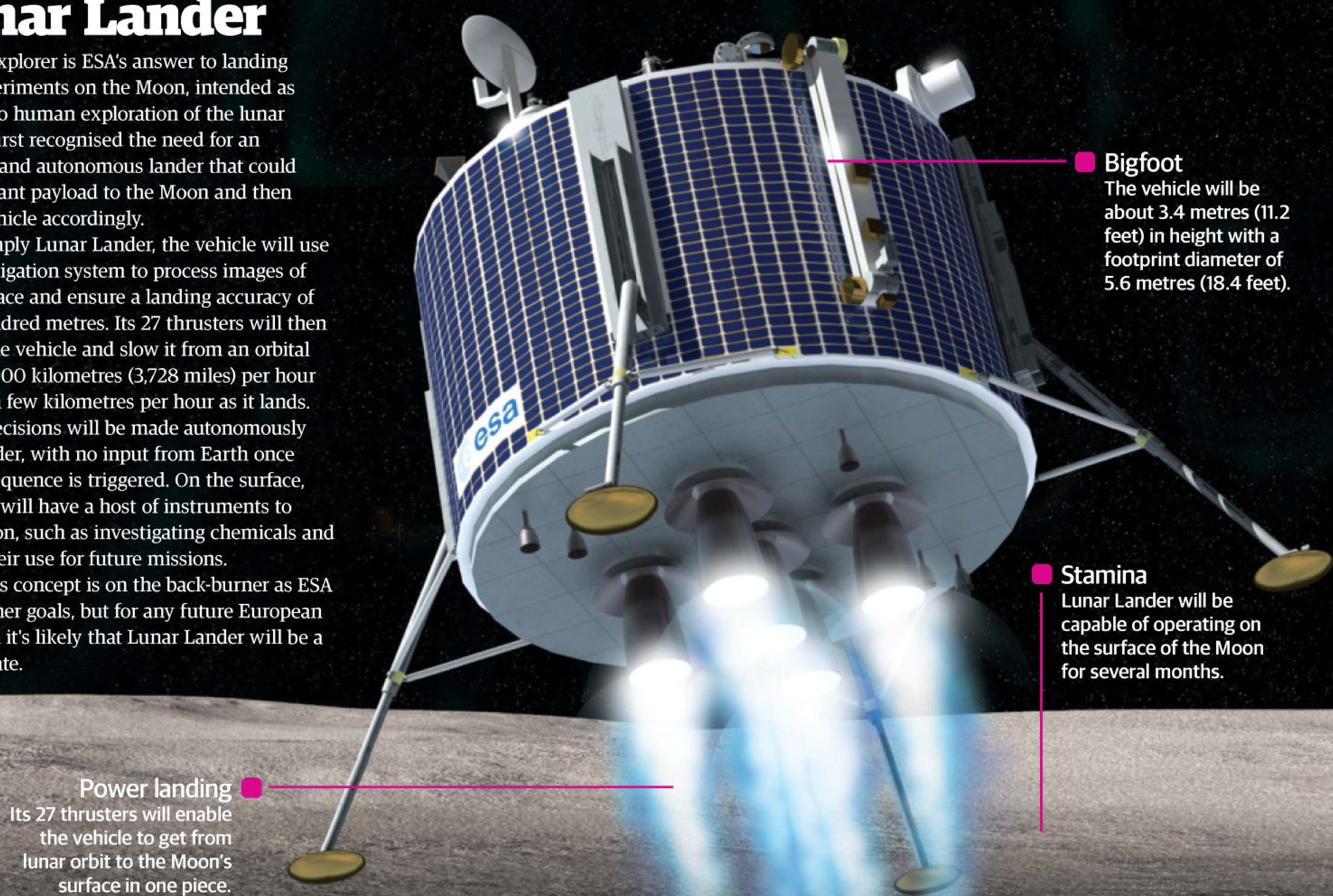
Engineers at NASA's Johnson Space Center have now tested a scale model of this innovative concept, successfully dropping a 0.9-kilogram (two-pound) capsule from 146 metres (480 feet) onto the floor. The ultimate goal is to enable a full-scale system to employ the technology and land accurately at any location in the world. The same concept could also be applied to spent rocket boosters, bringing them safely to Earth to be used again on another launch.

2 Lunar Lander

This robotic explorer is ESA's answer to landing scientific experiments on the Moon, intended as a forerunner to human exploration of the lunar surface. ESA first recognised the need for an accurate, safe and autonomous lander that could take a significant payload to the Moon and then designed a vehicle accordingly.

Dubbed simply Lunar Lander, the vehicle will use an optical navigation system to process images of the lunar surface and ensure a landing accuracy of just a few hundred metres. Its 27 thrusters will then manoeuvre the vehicle and slow it from an orbital velocity of 6,000 kilometres (3,728 miles) per hour down to just a few kilometres per hour as it lands. All of these decisions will be made autonomously by Lunar Lander, with no input from Earth once the landing sequence is triggered. On the surface, Lunar Lander will have a host of instruments to study the Moon, such as investigating chemicals and identifying their use for future missions.

For now this concept is on the back-burner as ESA focuses on other goals, but for any future European Moon mission it's likely that Lunar Lander will be a prime candidate.



Lunar Lander could be ESA's future method of getting scientific experiments onto the Moon

3 Reusable rockets

For decades we've relied on expendable rockets to reach space, with the boosters and tanks being disposed of on almost every occasion once their payload had reached orbit. It's a costly endeavour and one that SpaceX hopes to rectify with a revolutionary concept that could dramatically alter the launcher business and drastically reduce the cost of sending payloads into space. SpaceX is hoping to make rockets reusable so that everything launched can be recovered and used again on subsequent launches. For now it's only looking at returning the first stage of a rocket, but in the future it may be possible to return an entire rocket to Earth to be used for another launch.

The American company has been designing this so-called Grasshopper rocket technology for years by means of small hops off the ground, testing the possibility of using a controllable booster to return rockets to Earth after launch to be used again. Now it's nearing the point where this same technology can be tested on a fully fledged launch rather than the small jumps it has performed so far, but just how does it work? Take a look at our illustration to see how SpaceX plans to bring rockets back from the abyss.

> "In the future it may be possible to return an entire rocket to Earth"

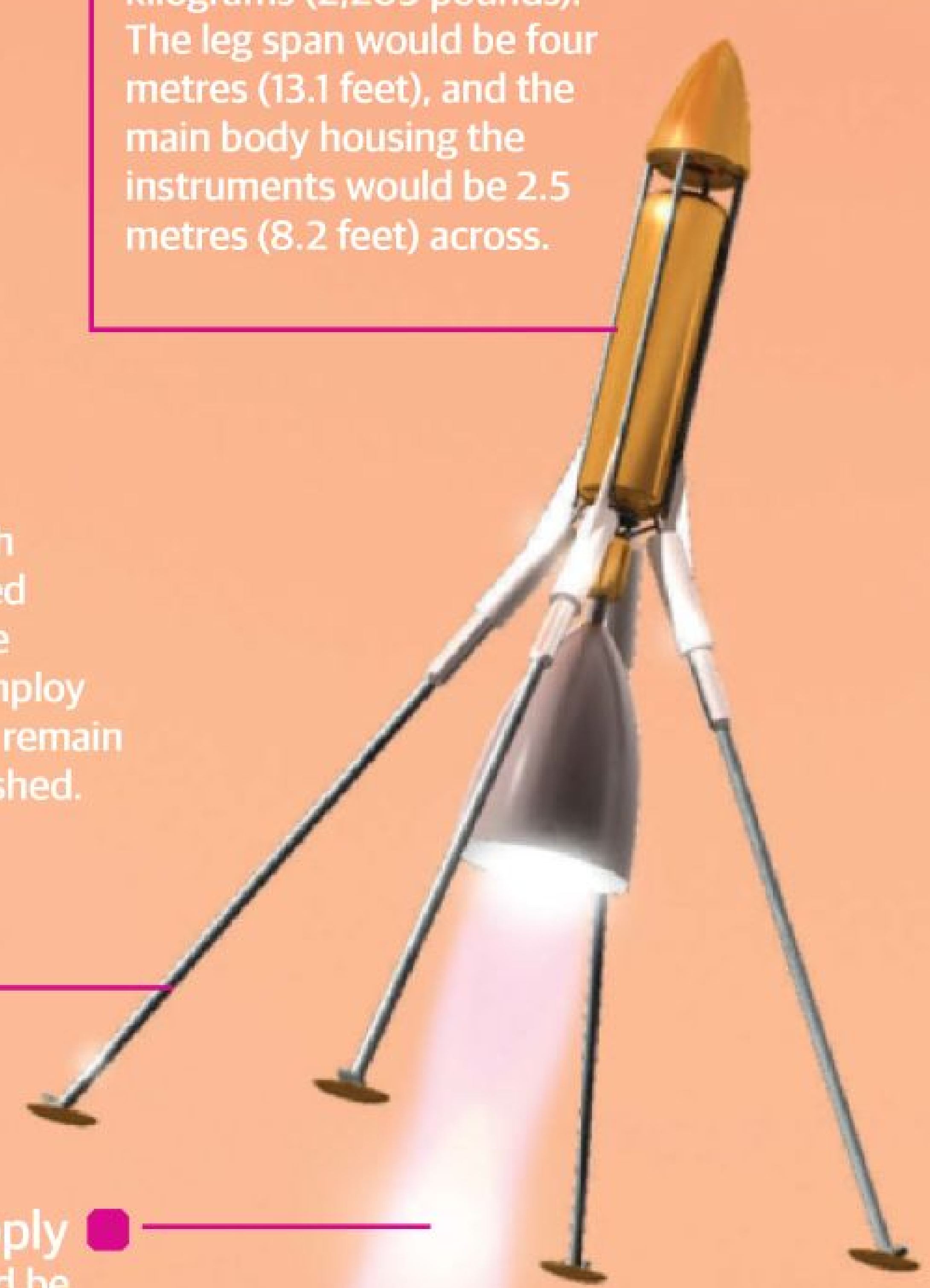
TOUCH DOWN ON THE RED PLANET

Some revolutionary designs for conquering Mars

Stability
The lander will use extendable legs to ensure stability as it touches down on the surface, with a landing accuracy of ten kilometres (6.2 miles).

Retrorockets
Red Dragon will land without parachutes, instead using a combination of drag from the Martian atmosphere and retro-propulsion thrusters to safely touch down on the surface.

Exclusive access
The use of thrusters will enable Red Dragon to touch down at sites inaccessible to vehicles using parachutes, such as areas of high elevation.



Big stride
The entire hopper would weigh about 1,000 kilograms (2,205 pounds). The leg span would be four metres (13.1 feet), and the main body housing the instruments would be 2.5 metres (8.2 feet) across.

Strong legs
In order to cope with the strain of repeated leaps, the legs of the Mars Hopper will employ magnets in order to remain rigid and not be crushed.

Infinite supply
Carbon dioxide could be gathered from the Martian atmosphere to be used as a propellant inside the vehicle, in order to jump to different destinations.

4 Red Dragon

Landing humans on the surface of Mars is something that is surely still decades away, but SpaceX has already begun to plan how it or another space-exploratioinon agency might be able to perform the feat.

The concept spacecraft is the Red Dragon, a modified variant of the Dragon capsule that has already successfully flown unmanned into Earth orbit and back. The capsule itself is rather spacious at 3.7 metres (12.1 feet) in diameter, with an interior volume of 11 cubic metres (388 cubic feet). Upon entering the Martian atmosphere, the capsule would use powerful retrorockets to slowly and safely lower itself to the surface without damaging the instruments or humans inside.

If a Red Dragon is one day sent to Mars, it's likely the first will be unmanned to test the technology, merely carrying instruments to be used on the surface of Mars, including a drill. For a future manned mission, this could be the vehicle that takes humans to the surface, although of course it would need to be accompanied by other vehicles, perhaps more Red Dragons, that would bring additional cargo and liveable habitats to the surface.

5 Hopper

Once you've landed on Mars, you're kind of stuck in that area, right? Well, what if you could take off and land again and again?

That's exactly what a team from the UK's Leicester University and the Astrium space company have envisioned, which they've dubbed the Mars Hopper. This lander would acquire propellants from the Martian atmosphere as it passed through, enabling it to perform hops of as much as a kilometre (0.62 miles) on the Martian surface.

Once on the ground, carbon dioxide from the air is compressed and liquefied, before being pumped into a chamber and exposed to intense heat from a radioactive source. This carbon dioxide would then explosively expand and could be fired out of a nozzle to propel the vehicle into the air again to repeatedly land in several different locations.

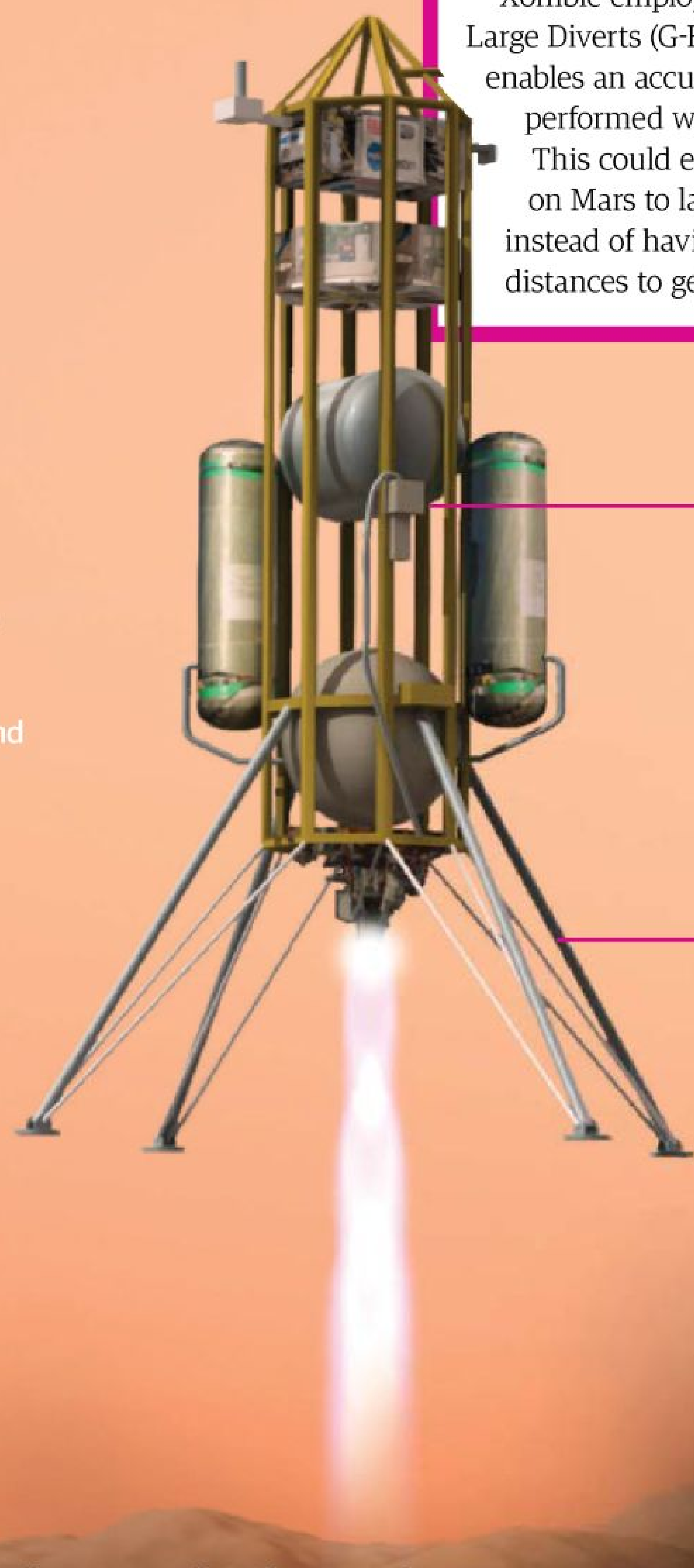
The benefits of such a technology are obvious; the Mars Hopper could leap across the surface, exploring many different locales of interest in a short amount of time, rather than confining itself to the landing site it initially touched down in.

6 Xombie

One of the biggest obstacles to landing on an alien world is accuracy. A lander needs to avoid potential obstacles such as rocks and craters, and it also needs to be able to touch down in a targeted area.

When NASA's Curiosity rover landed on Mars in August 2012, it had a radial landing accuracy of several kilometres, but Masten Space Systems' Xombie technology could significantly improve this accuracy six-fold using an innovative design.

Xombie employs Guidance for Fuel Optimal Large Diverts (G-FOLD), which in basic terms enables an accurate landing to be calculated and performed with only limited amounts of fuel. This could enable future robotic missions on Mars to land closer to features of interest, instead of having to drive extremely long distances to get to them.

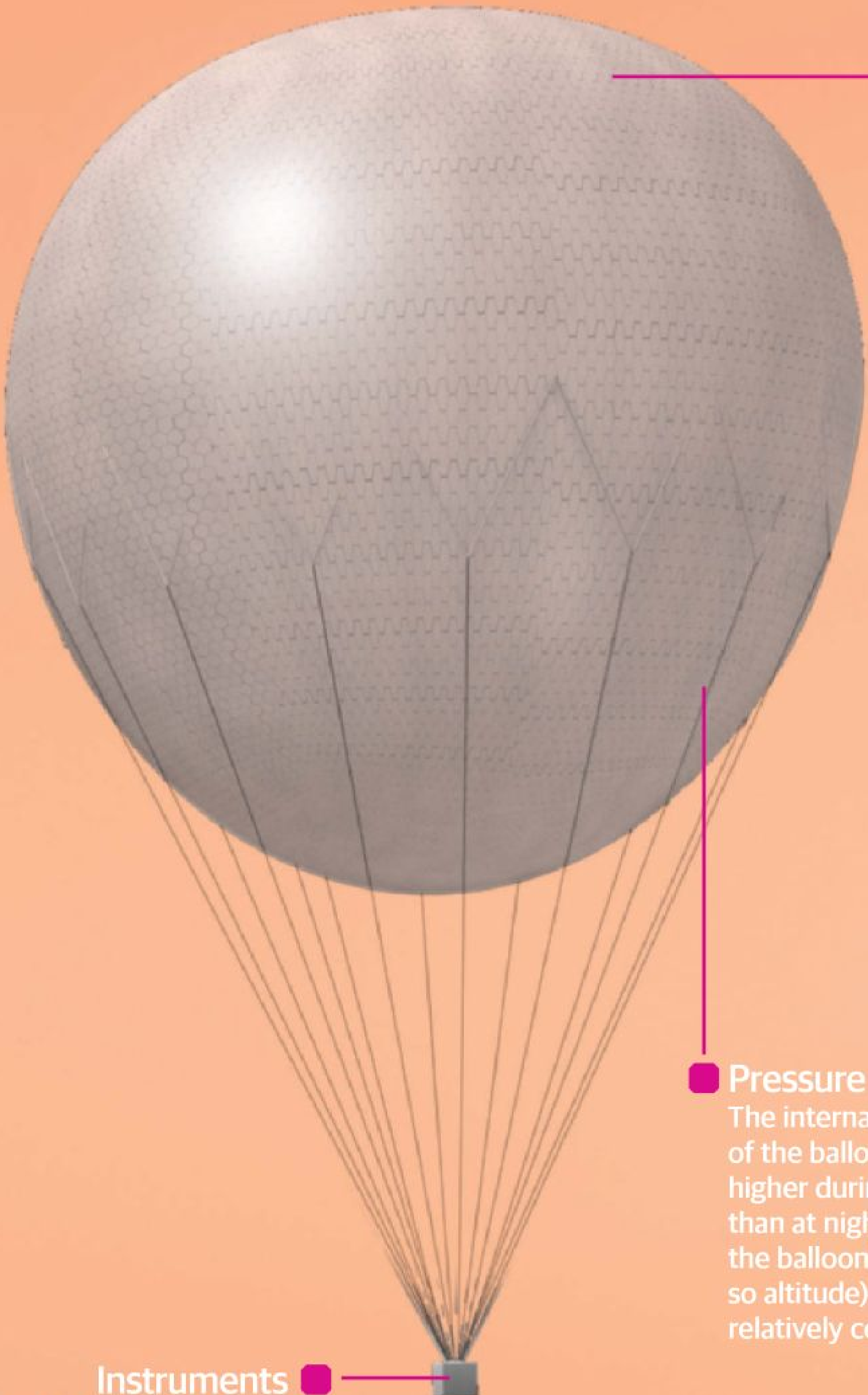


7 Shielded Mars Balloon Launcher

Using balloons to travel above the surface of Mars in order to study the planet has long been of interest, but exactly how to get the balloon there has been a conundrum. This particular technology, the Shielded Mars Balloon Launcher (SMBL), could be the answer.

Rather than putting a balloon directly into the Martian sky, this compact lander would touch down on the surface likely using parachutes. There, a structure would be extended and in it a balloon would be inflated. Attached to the base of the balloon would be an instrument package that would be carried into the sky in order to carry out tests from the air.

The proposed SMBL system is small enough, at a mass of just 15 kilograms (33 pounds), that it could piggyback as a secondary payload on a larger Mars mission.

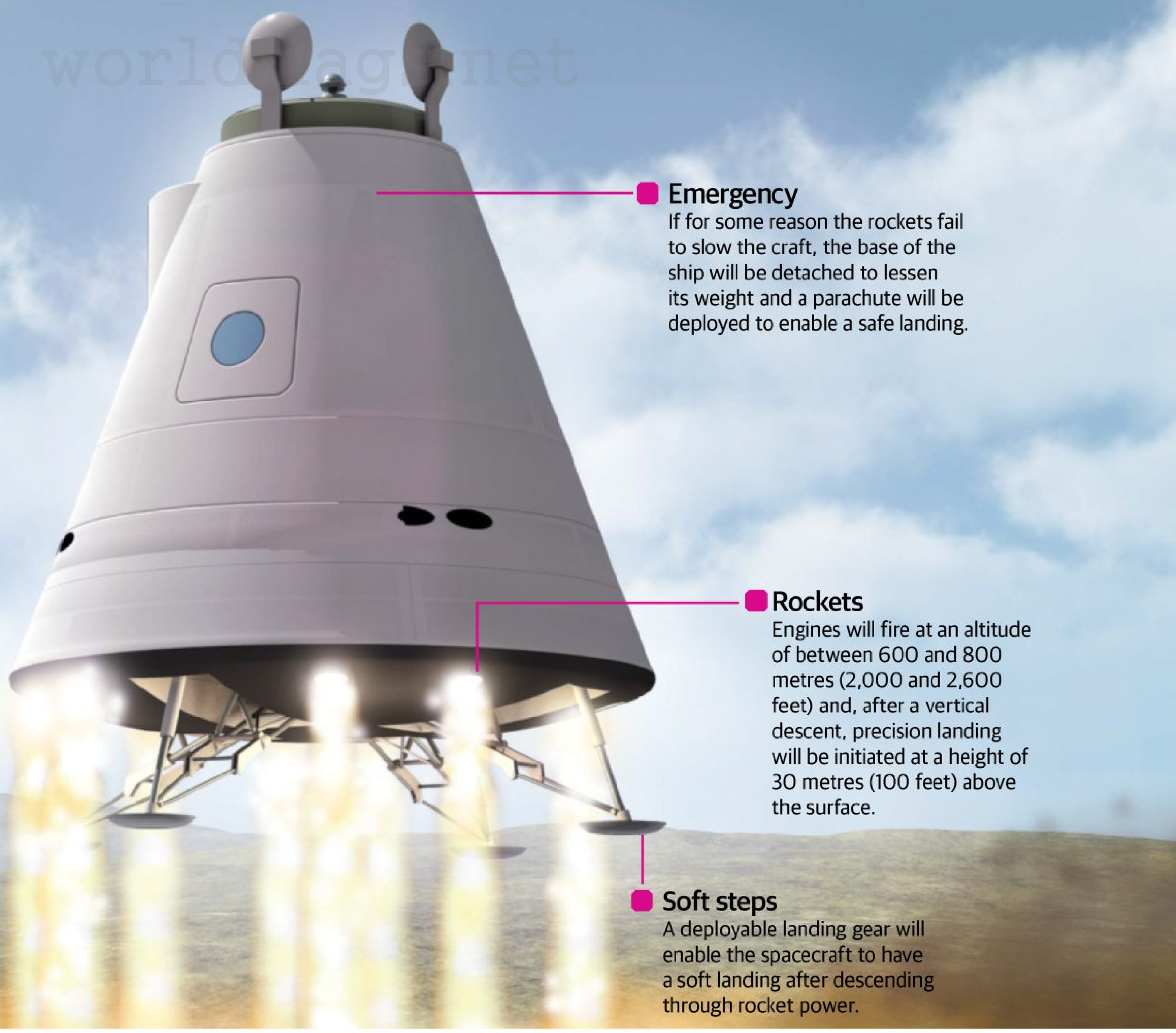


8 Next-gen Soyuz

When today's astronauts and cosmonauts return from the International Space Station, they do so in the Soyuz spacecraft. The vehicle descends through Earth's atmosphere before deploying parachutes and, a split second before touching the ground, boosters quickly fire to slow it down and give the crew a comfortable landing. It's a system that works well, but it's not exactly accurate.

The Russian space agency (Roscosmos) is looking into ways to utilise rocket power during the landing, enabling far greater accuracy. Known as the Prospective Piloted Transport System (PPTS), this spacecraft would use solid-propellant soft-landing engines to slow itself.

So far different versions of the vehicle have been designed for various purposes. An Earth-orbiting variant would carry a crew of six and be able to undertake 30-day missions by itself or a year if docked to the ISS. A lunar version, meanwhile, could carry a crew of four on a 14-day mission to lunar orbit.



9 Europa Submarine

When it comes to landing on other worlds in the Solar System, most require some vehicle capable of traversing a hard surface. Most, that is, apart from Europa, where there is believed to be a vast subsurface ocean containing more water than on the entire Earth, just waiting to be explored.

Various proposals have been drawn up to explore this underground ocean and one of the most exciting is a submersible vehicle that could journey under the ice, sending data back to its parent spacecraft. A submarine, such as one devised by professor Carl Ross at the University of Portsmouth in England, would need to be able to withstand the expected high pressures from the deep oceans, some as much as 100 kilometres (62 miles) deep, ten-times deeper than any oceanic trench on Earth. It would also need a fuel cell to power its propulsion systems in addition to its communications and scientific instruments.

The goal of the mission would be to discern if Europa's oceans harbour life, or at least have the potential to do so. Of course, such a mission is still decades away from coming to fruition, but perhaps our first vehicle to venture beneath Europa's icy surface will not be too dissimilar from this.

"The goal of the mission would be to discern if Europa's oceans harbour life"

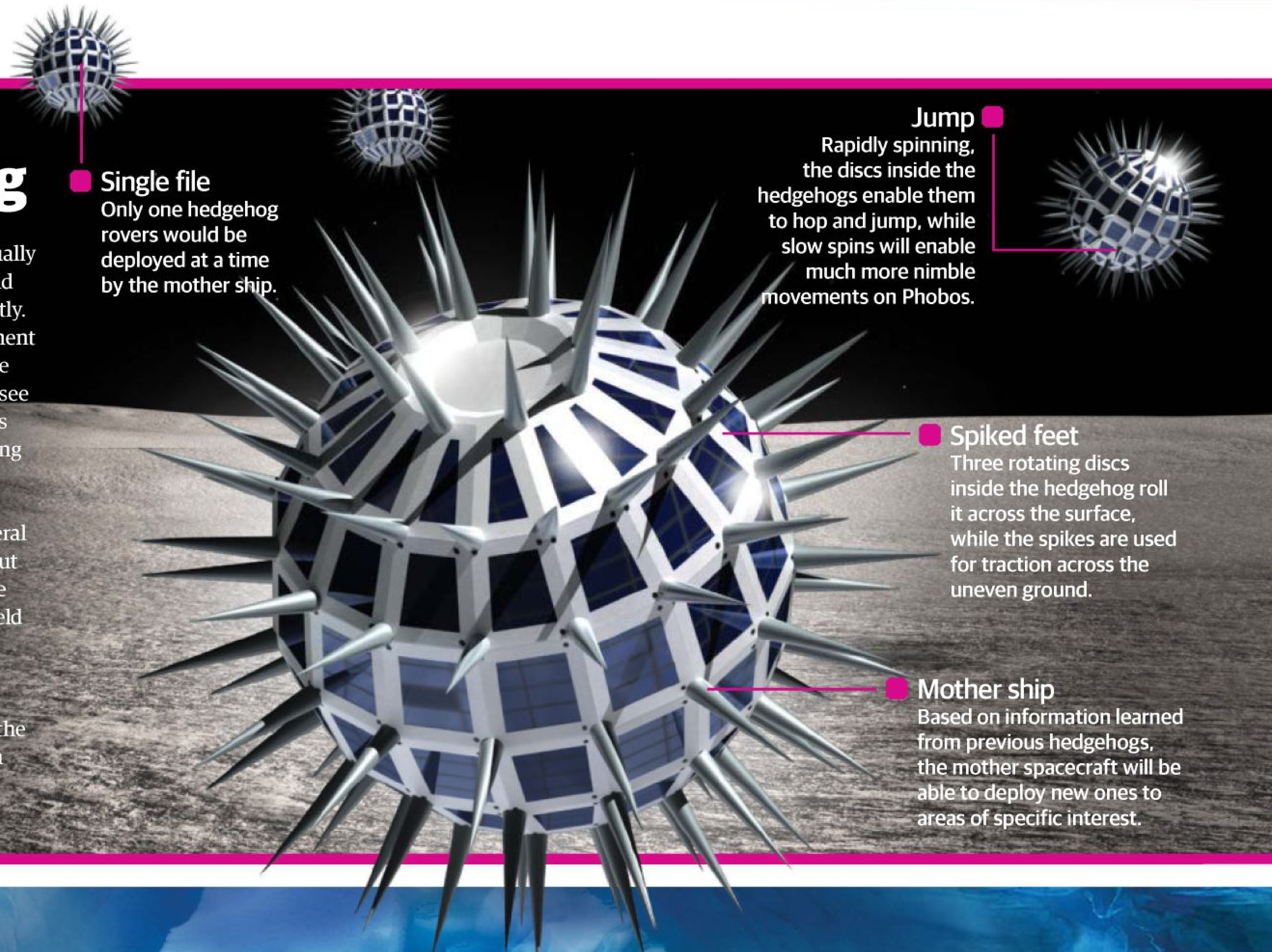
10 Space hedgehog

While Mars might steal most of the limelight, its moon Phobos is an equally interesting destination to explore and one that has garnered interest recently.

Researchers at Stanford's Department of Aeronautics and Astronautics have come up with a mission that would see spacecraft bounce and tumble across this Martian moon's surface, gathering scientific data along the way.

Carried by a mother spacecraft known as the Phobos Surveyor, several spiky and spherical rovers, each about half a metre (1.6 feet) wide, would be deployed on Phobos. Instruments held within the sphere would be used to perform a host of experiments.

While the Phobos Surveyor will perform large-scale measurements, the smaller vehicles gather detailed data from the surface. This could unveil clues about the origin of Phobos.



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